LIME-MICRONUTRIENT STUDIES WITH SOILS FROM COSTA RICA AND THE EASTERN LLANOS OF COLOMBIA

By

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To my parents,

Marci[illegible]

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LIME MICRONUTRIENT STUDIES WITH SOILS FROM COSTA RICA AND THE EASTERN LLANOS OF COLOMBIA

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Three Ultisols and one Oxisol from Costa Rica, and two Ultisols and two Oxisols from the eastern Llanos of Colombia were collected in 1972 for soil fertility studies. Surface soils (0-15 cm) were used for greenhouse experiments, and surface and profile samples were used for laboratory analyses.

Soils from Costa Rica had higher concentrations of nutrients than Colombian soils. On the other hand, Costa Rican soils contained smaller amounts of 1N KCl exchangeable Al.

An incubation trial with lime was conducted with all tropical soils to determine the effect of $CaCO_3$ on exchangeable Al and soil pH. Soils from Costa Rica required 800 ppm Ca to reduce exchangeable Al to 10 ppm or less. Colombian soils required higher rates of $CaCO_3$ than soils

[illegible]
[illegible]
200 ppm.

A prel[illegible] with three w[illegible]ason grasses o[illegible] Haplaquod) from Florida. Pangola d[illegible] *decumbens* Stent), Pensacola bahi[illegible] Flugge), and pearl millet [*Pennisetum typho*[illegible] Stapf and Hubbard] were grown successively. [illegible] ments were superimposed on soil without frit [illegible] Pensacola bahiagrass (bahia) harvest. Pearl [illegible] forage yields were increased through the hi[illegible], but Pangola digitgrass (Pangola) responded o[illegible] first $CaCO_3$ increment. Herbage yields of bahi[illegible] creased by liming only when frit was omitte[illegible] creased forage yields of Pangola and bahia at all l[illegible] but had no effect on millet yields. Furthermore, bahia yields were increased by the first Cu increment, but applied Cu did not affect millet growth. The data indicated that the critical Cu concentration in bahia forage was 2.5 ppm, and for millet it was 2.7 ppm or less.

All soils from Costa Rica and Colombia were used in the primary lime x frit greenhouse experiment. The SMP

buffer was used to select lime rates. The test plants were millet and Pangola. Phosphorus equal to the initial quantities was applied to two replications of all soils after the second Pangola harvest. Uniform applications of Mg were made to Colombian soils following the fifth, sixth, and seventh harvests. Lime application increased millet yields from the Oxisol from Costa Rica and from all Colombian soils. No growth response by millet to added frit was obtained. Frit increased and lime reduced forage micronutrient concentrations in millet. Pangola did not respond to lime or frit applications to Costa Rican soils, but extra P increased total Pangola herbage from one Ultisol and the Oxisol from Costa Rica. Forage yields declined markedly until additional Mg was applied, after which growth rate increased. Yields of Pangola were increased by liming one Oxisol and the two Ultisols from Colombia, while frit addition increased yields from one Oxisol. Addition of extra P to all Colombian soils increased total Pangola herbage.

A Zn x Cu factorial experiment with one Oxisol (Drainageway) and one Ultisol (East Carimagua) from Colombia was conducted. Pangola was the test plant. Copper applications to the Ultisol increased forage yields. Although

Zn did not significantly increase yields from this soil maximum growth was obtained when Zn and Cu were each applied at 5 ppm. Maximum yields from the Oxisol were obtained when Zn and Cu were applied at 5 and 60 ppm, respectively Application of 5 ppm Zn caused striking reductions in forage P and Mg concentrations. Results indicated that the critical Zn concentration in oven-dry Pangola forage was between 10 and 13 ppm, and Cu between 2.0 and 3.2 ppm.

INTRODUCTION

There is an increasingly urgent worldwide demand for more food, especially in developing areas. Since most rapid human population growth rates generally occur in developing regions, which are largely confined to the tropics, food production in these areas must be increased if minimum nutritional standards are to be met.

Because of high rainfall and high temperatures, many soils in tropical regions are highly weathered. Most bases in these soils have been leached and, in many instances, Al and/or Mn accumulate in the surface horizons at concentrations that are toxic to many plant species. Intense weathering has also deprived the soils of other plant nutrients such as N, P, S, and micronutrients. Currently many of these soils are undeveloped, but their requirements for enhanced productivity must be established.

Many soils in Costa Rica are of volcanic ash origin, and contain relatively large amounts of non-crystalline colloidal material such as allophane. Some of these soils are acid with high concentrations of exchangeable Al and/

or easily reducible Mn. Deficiencies of Zn, B, and Mn in coffee have been reported in some of these soils (Wander, 1962).

The Llanos of South America comprise an extensive region of relatively flat land. The area of the eastern Llanos of Colombia is approximately 30 x 10^6 ha (Molero-Mata, 1971). It consists of soils that are highly weathered, very acid, high in oxides of Fe and Al, and low in natural fertility. According to Molero-Mata (1971) the parent materials impart to these soils a uniform deficiency of weatherable minerals and exchangeable cations. However, high annual rainfall and high temperatures over long time periods have contributed to weathering and leaching of nutrients.

Only a small area of the eastern Llanos of Colombia is presently being used for commercial agriculture. Crops grown commercially include forage grasses, rice (*Oriza sativa* L.), cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), plantain (*Musa sapientum* L.), bananas (*Musa paradisiaca* L.), and cacao (*Theobroma cacao* L.). Some of these and other crops are also grown at a subsistence level (Molero-Mata, 1971).

The eastern Llanos has the potential of becoming an area that can contribute on a large scale to the economy and welfare of the Colombian people. Some advantages of this region are the good soil physical characteristics, level topography, freedom from flooding, low land cost, proximity to Bogota the capital, and presence of navigable rivers connected to the Atlantic Ocean (Guerrero-Munoz, 1972).

The importance of liming acid soils in temperate regions to improve plant growth is widely recognized. Likewise, the decrease in Zn, Cu, B, Fe, and Mn and the increase in Mo availabilities by liming acid soils are well documented. The response of tropical plants to lime on tropical soils, however, is variable, lime may be detrimental or it may markedly increase yields. Differential responses observed are associated with complex interrelationships among many soil factors, such as nature of clay minerals and amorphous fraction; toxic levels of Al and Mn; micronutrient deficiencies; P, Mg, and Ca availabilities, lime rates; effect on microbial activity; and plant species used.

There are marked differences among plant species, varieties, strains, and clones with regard to sensitivity to soil acidity and a long term approach may be to breed and select ecotypes for specific areas. However, a more immediate, positive approach to soil acidity is to use amendments such as $CaCO_3$, which will increase pH and reduce toxicities of Al and Mn. The problem is to establish suitable lime rates and to determine limiting micronutrients for intensified crop production.

Therefore, laboratory and greenhouse experiments were conducted with one soil from Florida and eight tropical soils, four from Costa Rica and four from Colombia, to study the effect of lime and micronutrients on growth and composition of pangola digitgrass (Digitaria decumbens Stent), Pensacola bahiagrass (Paspalum notatum Flugge), and pearl millet /Pennisetum typhoides (Burm) Stapf and Hubbard/, three important warm-season forage species, and to relate responses to chemical properties of the soils as they are influenced by lime. Effects on exchangeable Al and micronutrient availabilities were of special interest.

LITERATURE REVIEW

Soil Acidity and Plant Growth

Reviews of the nature of soil acidity have been made by Jenny (1961) and Coleman and Thomas (1967). Soil acidity is associated with the presence of exchangeable H and Al. It consists of two important factors, intensity and quantity. The intensity is characterized by measurement of the H^+ activity. Quantitative aspects are characterized by determining the amount of alkali required to titrate soil to a determined end point (Black, 1968).

Sources and Development of Soil Acidity

Acidity in soil arises from different sources and its intensity is largely controlled by ion exchange and other hydrolytic or absorptive reactions. Layer aluminosilicate minerals, hydrous oxide minerals, organic matter, and soluble acids are mostly responsible for soil acidity.

Layer aluminosilicate minerals

The total charge of these minerals originates from isomorphic substitution in the crystal lattice, or from dissociation of H^+ from hydroxyl groups or from bound water of constitution (Marshall, 1949; Tisdale and Nelson, 1966). Charges arising from isomorphic substitution are called permanent charges and are responsible for electrostatic bonding of cations (Schofield, 1949). Charges resulting from dissociation of H^+ are called pH-dependent charges and result in ionic covalent bonding. These charges can arise when structural OH^- at corners and edges of the clay lattice dissociate H^+ within the slightly acid to alkaline pH range. Amorphous Al-and Fe-hydroxy compounds, which in acid soils bear positive charges, may coat aluminosilicate clays blocking normal exchange sites. As soil pH increases these hydroxy complexes may hydrolyze and unblock exchange sites on the minerals (Schofield, 1949; Tisdale and Nelson, 1966). Hydroxy-Al and hydroxy-Fe coatings on layer silicates are responsible for much of the apparent pH-dependent charge of soils (Coleman and Thomas, 1967).

An equilibrium exists between H^+ and Al^{3+} in acid soils. As H^+ are produced they will in turn dissolve some Al from the clay mineral lattice. In a base unsaturated clay system, both H^+ and Al^{3+} are present as exchangeable ions. If a base is added to this system, the H^+ will be neutralized first. Upon addition of more base, the Al^{3+} begins to hydrolyze with the ultimate production of H^+ in amounts equivalent to the Al^{3+} present. At low pH values, most Al is present as the hexahydrated Al^{3+}. Jackson (1963) stated that below pH 5.6 the buffering capacity of a mineral soil depends primarily on exchangeable Al.

Hydrous oxide minerals

The main hydrous oxide minerals are oxides of Fe and Al. They may occur as amorphous particles of colloidal dimensions, as crystalline colloidal material such as gibbsite, as coatings on other mineral particles, or as interlayers between crystal lattice structure (Hsu and Rich, 1960). Major forms of amorphous inorganic materials that occur in soils are the hydrous oxides of Al, Mn, and Fe, either alone or combined (Mitchell, Farmer, and McHardy, 1964). The intergrade minerals are a group of clays resulting when hydroxides of Al and Fe precipitate in the cleavage spaces of expanding layer silicates

(Coleman and Thomas, 1967). The cation exchange capacity (CEC) of intergrade minerals usually is smaller than would be expected for uncoated layer silicates (Rich and Obenshain, 1955) Coleman and Thomas (1967) stated that removal of interlayer materials is accomplished by NaOH or fluoride solutions and results in increased CEC.

Mixed gels containing primarily silica and alumina in mole ratio usually between 0.5 and 1.3 are called allophane; they occur extensively in soils derived from volcanic ash materials (van Olphen, 1971; Mitchell et al., 1964). Allophane is probably the only oxide mineral (excluding interlayer hydrous oxides) which plays a direct role in buffering soils and contributes to the chemistry of soil acidity (Coleman and Thomas, 1967). Allophane has a large surface area, high CEC, high anion exchange capacity (AEC) and is very reactive. Wada and Ataka (1958) studied the AEC and CEC for some clay materials, separating both coulombic and non-coulombic adsorption. Coulombic adsorption is the normal ion exchange reaction and is equivalent to the number of positive or negative sites on the mineral lattice, whereas non-coulombic adsorption is the salt held in the interstitial solution and involves equivalent amounts of cations and anions. These investigators found that ion uptake by montmorillonite-illite clay was predominantly by coulombic adsorption. The AEC was only 2% of the CEC and quite independant of the concentration of the equilibrating solution. In contrast, allophanic clay soils had both positive and negative charges even at pH 7.0. The greater parts of the CEC and AEC were due to non-coulombic adsorption, and CEC was considerably reduced as pH declined from 7.0 to 5.0 The properties mentioned above make allophane a very important soil constituent. Besides its importance in soil acidity, allophanic materials are important in the chemisorption of inorganic fertilizers and frequently make large fractions of the added fertilizers unavailable to plants (van Olphen, 1971), especially P, S, and possibly M

Organic matter

Microbiological decomposition of organic residues brings about the formation of humus. This material is an intermediate step in the decomposition process and contains several types of functional groups which are capable of attracting and dissociating H^+. Among these are carboxyl, phenolic, and amino groups. These contribute to the pH-dependent charge and, in sandy soils, may comprise more than 90% of the CEC. Humus may also react with Fe and Al ions to form complexes which may subsequently undergo hydrolysis to yield H^+. Breakdown and mineralization of organic matter and humus will release water, CO_2, salts, and acids. Increased CO_2 concentration, hydrolysis of acid salts, and organic acids produced contribute to soil acidity (Seatz and Peterson, 1964).

Soluble acids

Soluble inorganic and organic acids may be produced through biological activity from litter or other plant material and by application of acid forming fertilizers. Nitric and sulfuric acids accumulate after applications of ammonium and sulfur containing fertilizers. Addition of monocalcium phosphate also increases soil acidity (Coleman and Thomas, 1967).

Kohnke (1950) and Moorman (1963) observed increased concentrations of H_2SO_4 and reduced pH values when soils containing FeS (Cat Clays) were drained and exposed to oxidizing conditions. These soils are generally formed in deposits high in organic matter containing appreciable amounts of inorganic material which dissolve in the H_2SO_4 to yield large amounts of soluble

Al, Mn, and Fe (Coleman and Thomas, 1967) After submergence, the soil pH rises following precipitation of Al hydroxide, and reduction of Fe^{3+} and adsorption of Fe^{2+} by clays (Cate and Sukhai, 1964).

Aluminum and soil acidity

The importance of soil acidity in plant nutrition has been recognized for many years. However, concepts of the nature of soil acidity as well as methods for determining it have changed throughout the years.

Originally, it was believed that H^+ was the only cause of soil acidity. This concept led Woodruff (1947) to the development of a "soil limemeter," an instrument designed to determine lime requirement based on the exchangeable H. The same investigator (1948) stated that "the exchangeable H content of the soil is one of the best measures of the amount of limestone required by lime-deficient soils."

New concepts of the causes of soil acidity and methods to determine it have been developed based on present ideas of the nature of soil acidity. The importance of Al in the exchangeable portion of soil acidity has been demonstrated by Schofield (1949), Harward and Coleman

(1954), Jackson (1963), and others. Low (1955) proved that H- as well as Al-saturated clays could be prepared and that they have different properties. This finding was very important in explaining that soil acidity results from both H and Al ions. Harward and Coleman (1954) assumed that the Al adsorbed on clays was basically in the form of an exchangeable monomeric hydrated ion; however, Coleman and Thomas (1964) found that polymeric non-exchangeable Al- and Fe-hydroxy ions, in addition to exchangeable Al^{3+}, contribute greatly to buffer capacity in many soils.

Coulter (1969) indicated that acid soils have weak acid characteristics because of the hydrolysis of adsorbed Al, resulting in behavior similar to Al-saturated systems. He demonstrated that H-saturated clays have strong acid character, and with time, they are converted to Al-saturated systems. Transformation of H-bentonite to Al-bentonite was investigated by Davis, Turner, and Whittig (1962).

Several investigators have found correlations between pH and exchangeable Al. Yuan (1963) found a direct relationship between pH and $AlCl_3$ in aqueous solutions. Similarly, Popenoe (1966) observed a close relationship between exchangeable Al and pH in soils from Guatemala. He found significant amounts of exchangeable Al only in soils with pH values less than 5.0. However, excessive exchangeable Al does not occur in all acid soils. Clark and Turner (1965) did not find a direct relationship between either NH_4OAc (pH 4.8) extractable or exchangeable Al and pH in some acid soils. Appreciable amounts of H are present only in very acid soils or in combination with large amounts of organic matter. Yuan (1963), investigating acid, sandy soils in Florida where exchange properties are dominated by organic matter, found that H^+ sometimes exceeds Al^{3+} as the titratable acidity removed with 1N KCl.

Classification of Soil Acidity

Soil acidity can be conveniently classified as active and potential acidity (Coleman and Mehlich, 1957; Russell, 1961). The sum of exchangeable acidity and pH-dependent acidity constitutes total titratable acidity of the soil. Mehlich (1941) developed a method for measuring total acidity. The soil is extracted with $BaCl_2$-triethanolamine buffered at pH 8.2 and the extract is titrated with standard acid. Exchangeable acidity is the portion of the soil acidity that can be replaced with a neutral, unbuffered salt such as KCl (Coleman, Weed, and McCracken, [illegible] This portion of the soil acidity consists of Al and H ions adsorbed electrostatically on the exchange sites of the soil materials. Several investigators have reported that monomeric Al^{3+} is the main component of the exchangeable acidity (Coleman and Thomas, 1967, Schofield, 1949 Harward and Coleman, 1954 Coleman et al., 1959, Lin and Coleman, 1960, McLean, 1965, Schofield, 1949).

Nonexchangeable acidity has been termed pH-dependent acidity by Coleman et al. (1959) and Pratt (1961). It can be extracted by $BaCl_2$-triethanolamine at pH 8.2 after extraction with KCl (Pratt, 1961).

The proportion of exchange acidity in acid soils containing large amounts of organic matter is usually low. Coleman and Thomas (1967) attributed this low exchange acidity to the low CEC of organic matter in very acid soils. Aluminum- and Fe-hydrous oxides, either as surface coatings or in interlayer spaces of clays, reduce the proportion of exchangeable acidity (Lin and Coleman, 1960).

In some cases pH-dependent acidity can be attributed to organic matter. However, in many instances soils or subsoils with a low content of organic matter may show a high proportion of pH-dependent acidity (Pratt, 1961.

(Coleman et al., 1959). This is [illegible] for soils in the Ultisol and Oxisol orders (Coleman et al., 1959) which are probably the most abundant soils in many tropical regions

Measurement of Soil Acidity

Soil reaction is generally measured by the pH determination. Other aspects of soil acidity are characterized by titration curves. Lime requirement which is determined by estimating soil acidity is an important aspect of production programs in acid soils.

Soil pH

Soil reaction refers to the degree of acidity or alkalinity of a soil solution and is expressed as pH, a function of the H^+ concentration. pH is defined as the negative logarithm of the H^+ activity in g/liter and is affected by factors such as soil-water ratio, total soluble salts, and CO_2 concentration. A 1 to 2.5 soil-water ratio was adopted in 1950 by the Soil Reaction Committee of the International Society of the Soil Science (Peech, 1965). Soil pH is an important indicator of the general conditions of the soil and is one of the standard criteria for soil characterization. However, interpretation of soil pH regarding acidity is complicated by the complexity of the soil system.

Generally as the soluble salt concentration increases the measured pH decreases. Presumably the cation in the salt will undergo cation exchange with exchange acidity in the soil to release acid into the soil solution (Seatz and Peterson, 1964). Russell (1961) explained the salt influence on pH as an effect on the electric double layer around soil particles. Ions from the dissolved salt mix with exchangeable cations in the double layer and make it less diffuse. This causes a reduction in H^+ concentration across the double layer, with subsequent decrease in pH of the suspension. The salt effect has been reduced or eliminated by using a salt solution rather than distilled water for making soil pastes or suspensions. The salts more commonly used for this purpose are 1N KCl and 0.01M $CaCl_2$. The 0.01M $CaCl_2$ solution for measuring soil pH was proposed by Schofield and Taylor (1955). A 0.01M $CaCl_2$ solution is approximately equivalent to the total electrolyte concentration of the soil solution of a non-saline soil at optimum field water content (Schofield and Taylor, 1955). The pH value measured in 0.01M $CaCl_2$ may be 0.5 pH unit lower at low pH values than that measured in water (Russell, 1961).

Titration curves

Potentiometric titration curves are very useful in investigating the nature of soil acidity. An initial inflection point attributed to H^+ is observed as base is added, followed by a buffered region attributed to the presence of exchangeable Al precipitated as $Al(OH)_3 \cdot 3H_2O$ (Chao and Harward, 1962; Marshall, 1964; and Yuan, 1963). Coleman and Thomas (1964) showed marked buffering in the pH range 5.0 to 8.0 when montmorillonite complexed with Al- and Fe-hydrous oxides was titrated with NaOH in 1N NaCl. Soils relatively free of organic matter have representative buffer characteristics when dominated by monomeric exchangeable Al. Clays show the same buffer characteristics when H-saturated clays are compared with Al-saturated clays (Chao and Harward, 1962; Low, 1955; Marshall, 1964; Shainberg and Dawson, 1967; and Yuan, 1963). Rich (1970) found little difference in potentiometric titration curves developed by titrating $AlCl_3$-treated Dowex-50, vermiculite, and montmorillonite with NaOH and $Ba(OH)_2$.

Zelazny and Fiskell (1971) used potentiometric titrations with $Ba(OH)_2$ to study acidic properties of some soils from Florida. They concluded that acidity from the soils studied was derived from exchangeable Al at low pH and from H formed by release of protons from partially neutralized Al and organic matter as pH increased.

Conductimetric titration curves have also been used extensively in distinguishing the acidity produced by H and Al. Marshall (1964) reported a linear decrease in the titration curve similar to that of strong acids and a linear middle section close to that of a weak acid when titrating a mixture of HCl and $AlCl_3$ in a clean system. The first inflection point corresponded to exchangeable H and the length of the linear middle section corresponded to exchangeable Al. He stated that when H-clays are titrated with a base the conductivity decreases because of higher H^+ mobility as compared to cations of the base until all H^+ is neutralized. Conductivity then rises rapidly as OH^- concentration increases because of mobility of these ions. Aluminum-clays have little free H^+ present and when they are titrated with NaOH the conductivity rises with the increased mobility of the OH^- added. Dewan and Rich (1970) used conductimetric titrations to study the sources of acidity in several acid soils. In titration with $Ba(OH)_2$ and NaOH, consistent results were obtained when they took into account the aluminate reaction. The extent of the aluminate reaction for exchangeable interlayer Al depended on the exchange of Al^{3+} by the base. The lower values for NaOH compared to $Ba(OH)_2$ were attributed to poor exchange of Al^{3+} by Na^+. All the exchangeable Al extracted by KCl was in the Al^{3+} form.

Kissel and Thomas (1969) used conductiometric titration with $Ca(OH)_2$ to estimate total acidity. They stated that when acid soils are interlayered with hydroxy-Al, the resulting titration curve with NaOH does not allow a distinction between exchangeable and the non-exchangeable acidity caused by hydroxy-Al. However, the use of $Ca(OH)_2$ provides a reasonable and rapid estimation of exchangeable Al^{3+} and the total acidity.

Coleman and Thomas (1964) stated that erroneous conclusions about the true strength of soil acids can be obtained with titration curves of clays, organic matter, and whole soils. They demonstrated that the buffer curves for an Al-peat lie well above that for H-peat, and that Al-saturated material has a smaller buffer capacity, to pH 7, than H-saturated material. Martin (1960) found the weak acid behavior of organic matter to be caused by entrained Fe and Al ions or hydroxy Fe and Al ions since such complexes, rather than free carboxyl groups, occur in acid soils. At low pH values, reaction of soil organic matter with base involves hydrolysis of bound trivalent metal ions rather than ionization of free carboxyl groups.

Lime requirement

Soil pH and percent base saturation have been used to determine lime requirement (Mehlich, 1941). However, this method has limited use because the relationship between pH and percent base saturation varies from soil to soil.

Bradfield (1942) developed a titration method by which $Ca(OH)_2$ increments are added to soil suspension to estimate lime requirement. The titration curve levels off at pH 8.2, with the intersection of ascending and horizontal lines corresponding to Ca saturation, and the amount of $Ca(OH)_2$ added to reach that condition is equivalent to the soil acidity.

Potentiometric titrations of soil with hydroxides of Na, Ca, and Ba have been used to determine total soil acidity and lime requirement, but the reaction near neutrality is slow and there is the possibility of side reactions which restrict the use of this procedure (Coleman and Thomas, 1964).

Leaching with buffer solutions is widely used to measure total soil acidity and lime requirement. Mehlich (1948) used $BaCl_2$-triethanolamine at pH 8.2 to determine total acidity. Paranitrophenol buffered at pH 7.0 was suggested by Schofield (1933), while Woodruff (1948) used a mixture of $Ca(OAc)_2$-paranitrophenol-MgO buffered at pH 7.0. The buffer solution is mixed with the soil and lowers its pH by 0.2 unit for each ton of lime required by the soil. Shoemaker, McLean, and Pratt (1961) modified Woodruff's method. They claimed the new method (SMP) was adequate to estimate lime requirement of some acid soils from Ohio with appreciable amounts of extractable Al.

A new approach to liming acid soils has been proposed by Reeve and Sumner (1970) and Kamprath (1970). They suggested the use of lime only to neutralize exchangeable Al in the soil and supply Ca and Mg. Kamprath (1970) recommended liming at a rate equivalent to 1.5 times the exchangeable Al for more tolerant plant species and to 2.0 times for plants very sensitive to Al. The factors 1.5 and 2.0 are expected to reduce Al saturation to approximately 15 and 5%, respectively. Black (1968) stated that total titratable acidity is not the appropriate measurement for determining lime requirement because the response of plants is determined primarily by intensity of soil acidity and not by quantity.

Neutralization of soil acidity

Limestones, either calcitic ($CaCO_3$) or dolomitic $[CaMg(CO_3)_2]$, are sparingly soluble in pure water but they become soluble in water containing CO_2 — the greater the partial pressure of CO_2 in the system, the more soluble limestone becomes (Seatz and Peterson, 1964).

Upon dissolution of $CaCO_3$, Ca displaces H^+ and Al^{3+} from exchange sites by mass action. Aluminum hydrolyzes and produces more H^+. Seatz and Peterson (1964) implied that bicarbonate ions react with H^+ to neutralize the acidity. However, this may be an oversimplication of the reaction between HCO_3^- and water with the production of H_2CO_3 and OH^-, the latter reacts with the H^+ to neutralize the acidity. The reactions may be represented as follows:

1. Dissolution of $CaCO_3$ (Seatz and Peterson, 1964)

   $$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^-$$

2. Displacement of H and Al ions

   $$R\text{-}H + Ca^{2+} + H_2O \rightarrow R\text{-}Ca + H^+ + H_2O$$

   $$R\text{-}Al + Ca^{2+} + 6H_2O \rightarrow R\text{-}Ca + Al(H_2O)_6^{3+}$$

3. Hydrolysis of Al ions

$Al(H_2O)_6^{3+} + H_2O \rightarrow Al(H_2O)_5(OH)^{2+} + H_2O + H^+$

$Al(H_2O)_5(OH)^{2+} + H_2O \rightarrow Al(H_2O)_4(OH)_2^{+} + H^+ + H_2O$

4. Neutralization of H ions

$H^+ + H_2O + HCO_3^- \rightarrow H_2CO_3 + H_2O$

$H_2CO_3 \rightarrow H_2O + CO_2$

Or $H_2O + HCO_3^- \rightarrow H_2CO_3 + OH^-$

$H^+ + OH^- \rightarrow H_2O$

It is possible that complete neutralization of Al ions with formation of $Al(OH)_3$ does not occur below pH 6.0; as the neutralization proceeds hydroxy-Al ions start to polymerize (Hsu and Bates, 1964; Jackson, 1963).

Jackson (1963) indicated that below pH 5.6 the buffering capacity of mineral soils depends primarily on exchangeable Al, although exchangeable H can also contribute to soil acidity in some soils (Yuan, 1963).

Kamprath (1970) reported that lime addition of less than the amount required to neutralize the exchangeable acidity of four Ultisols from North Carolina reacted primarily with exchangeable Al causing the average pH to change from 4.6 to 5.3. Lime at a rate between 1.0 and 1.5 times exchangeable Al equivalent reacts with approximately equal quantities of exchangeable and nonexchangeable acidity. Lime in excess at 1.5 times the exchangeable Al equivalent reacts solely with nonexchangeable acidity such as H from Al- and Fe-hydrous oxides and carboxyl groups of organic matter

Plant Growth

An extensive review of the physiological effects of soil acidity on plant growth was made by Jackson (1967). Causes of poor plant growth on acid soils have been attributed to H^+, Al^{3+}, and Mn^{2+} toxicities, nutrient deficiencies, particularly low Ca and P levels, and reduced microbial activity. These factors may act alone but in many instances individual effects can not be separated.

Effect of hydrogen ion

Poor plant growth caused by H^+ activity has been reported. Arnon and Johnson (1942) found that lettuce (Lactuca sativa L.), tomato (Lycopersicum esculentum Mill), and bermudagrass [Cynodon dactylon (L.) Pers.] failed to develop to any extent at pH 3.0 in nutrient solutions. Good bermudagrass growth was obtained at pH values from 4.0 to 8.0; while lettuce and tomato developed well between pH 5.0 and 7.0. Poor growth was obtained at pH 9.0. Additional Ca in the nutrient solution resulted in marked improvement in growth at pH 4.0 and 5.0. Similar decrease in toxicity of H ions by Ca has been obtained by Sutton and Hallsworth (1958).

Losses of previously absorbed ions from excessive H^+ at pH below 4.0 have been found. Jacobson, Moore, and Hannapel (1960) reported marked losses of K from roots exposed to acid solutions. Hydrogen ions may increase cell membrane permeability and allow diffusion of cell constituents. Losses of inorganic and organic P, and soluble N from barley roots have also been reported (Moore, 1974). Jacobson et al. (1960) reported that Ca and other polyvalent cations protect root tissue from injurious effects of low pH.

Since the lower pH range for most agriculturally important soils is about 4.0, it can be assumed that excess H^+ is not the primary toxic factor in most soils. Jackson (1967) stated that excess H^+ is not the main cause of poor plant growth at pH values higher than 4.0, provided that adequate nutrient supply is maintained and Al and Mn are not excessive

Effect of aluminum

Numerous studies on the depressing effect of Al on plant growth have been published. However, beneficial effects of Al on plant growth have also been reported. Hortenstine and Fiskell (1961) showed a slight improvement in sunflower (*Helianthus annuus* Mill.) growth with the addition of 4 ppm Al in solution. Chenery (1955) reported that tea bush /*Camelia sinnesis* (L.) O. Kuntze/ required Al for normal growth; this plant has been shown to accumulate as much as 4% of Al in the dry matter. Chenery (1955) noted that Al accumulating plants have very acid cell saps (pH 4.3 to 4.8) and that their normal metabolic processes do not seem to be affected by high amounts of Al.

McLeod and Jackson (1965) obtained increased growth of alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.) seedlings by Al concentrations of 0.1 and 0.2 ppm in nutrient solution. Vidal and Broyer (1962) reported that Al stimulated Mg uptake by corn; and Bertrand and deWolf (1968) concluded that Al is actually required by corn with optimum concentrations between 0.25 to 0.30 ppm in nutrient solutions.

Lee (1971a,b) observed stimulation of vegetative growth and in some cases increased uptake of Mg and K by Irish potatoes (Solanum tuberosum L.) by addition of 1 to 5 ppm of Al; however, 20 ppm Al decreased the overall yield of potato tubers. Foy (1974) speculated that the mechanism by which small amounts of Al benefit plant growth may be related to increased Fe solubility and availability in the growth medium, resulting from hydrolysis of Al and lower pH.

According to McCart and Kamprath (1965), Al toxicity does not occur in soils above pH 5.5, but it is common at lower pH values. It is especially severe in most soils below pH 5.0, where more than half the cation exchange sites may be occupied by Al (Evans and Kamprath, 1970).

Several investigators have reported that Al toxicity is the most common factor limiting plant growth on acid soils (Foy and Brown, 1963, 1964; Foy et al., 1965; Jackson, 1967; Kamprath, 1970). Severity of Al toxicity is greatly modified by the presence of other ions. The effect of a given concentration of Al on plant growth will vary also with plant species, variety, and stage of plant development. Vidal and Broyer (1962) reported that Al concentrations in solution of 4 to 17 ppm were toxic to corn when Mg concentration was 10^{-4} M; however, the toxic effect disappeared [illegible] the Mg concentration was raised to 10^{-2} M.

Evidence of Al toxicity from field experiments is mostly indirect, consisting of correlation between exchangeable or extractable Al in the soil and plant growth (Abruna-Rodriguez et al., 1970, Kamprath, 1970). Although most evidence of Al toxicity in soils is generally indirect, Vlamis (1953) demonstrated with very careful experiments, that Al toxicity was responsible for poor plant growth on acid soils.

Adams and Lund (1966) found that the pH at which exchangeable Al becomes soluble in toxic concentrations varied with different soils. Similarly, levels of exchangeable Al required for toxicity varied among soils. They observed that Al was toxic at higher pH values and at lower levels of exchangeable Al in Norfolk subsoils, containing predominantly kaolinitic clay minerals, than in Dickson and Bladen, whose major clay mineral components are vermiculite and montmorillonite, respectively. Differences in critical pH values of soils have been attributed by Richburg and Adams (1970) to differences in the relationship between the pH of soil-water suspensions and the pH of displaced soil solutions. For example, Lucedale soils, with a critical pH of 5.1, had higher $Al(OH)_3$ activity than [illegible] and Magnolia, with critical pH of 5.5. The Lucedale subsoils also had the highest displaced solution pH

According to Welch and Nelson (1950) organic soils have lower critical pH values for normal crop development than mineral soils. Addition of organic acids prevented Al toxicity of alfalfa in nutrient solutions (Brogran, 1967). Evans (1968) reported that Al toxicity is infrequent at pH 5.0 in organic Coastal Plain soils of the eastern United States. His work indicated that the lower critical pH values for plant growth in organic soils compared with mineral soils is due, at least in part, to Al-organic matter complexes.

According to Foy (1974), Al toxicity in plant tops is usually characterized by symptoms resembling those of P deficiency (overall stunting, small, abnormally dark green leaves; purpling of stems, leaves, and veins- and yellowing and death of leaf tips), or of Ca deficiency (cupping or rolling of young leaves and collapse of plant apex or petioles).

Roots injured by excess Al are characteristically stubby and spatulate in appearance. Root tips turn brown and growth is inhibited. The whole root system is coralloid in appearance, having many inhibited and thickened lateral roots but lacking in fine branching (Fleming and Foy, 1968).

Considerable accumulation of Al occurs in the roots of most crop plants growing in acid soils (Jackson, 1967). Staining techniques indicate that Al accumulates on the root surface and in the cortex under conditions of toxicity (Black, 1968). He stated that the most obvious effect of Al toxicity is possibly inhibition of root growth. Inhibition of cell division by toxic Al levels has been indicated by an abnormally large number of cells with two nuclei in the meristematic region (Rios and Pearson, 1964).

Foy and Brown (1963, 1964) reported that P deficiency is the most characteristic symptom of Al toxicity in cotton plants. These investigators observed that as the pH was increased, Al was precipitated, and the plants absorbed more P, Ca, and K with subsequent increases in yields. These authors stated that at pH 4.0 enough P must be supplied to precipitate Al and have a P:Al ratio in solution $>$ 2. If the ratio was $<$2, severe P deficiency symptoms were observed in cotton plants.

Work by Clarkson (1966) suggested that the interaction between Al and P was an adsorption-precipitation reaction at the cell surface or in the free space of the root resulting in fixation of P. Rasmussen (1968), using an electron microprobe X-ray analyzer, found that P and Al precipitated on the surface of root epidermal cells. The root caps were freely permeable and contained the highest concentration of Al and P. The epidermal layer behind the root cap prevented movement into the cortex and conductive tissue. Clarkson (1967) showed that most Al assimilated by roots became strongly bound to adsorption sites in the cell wall. McCormick and Borden (1972) used the molybdenum-blue staining technique to study the site of P fixation by plant roots. They found that Al caused P to concentrate at root surfaces and in the epidermal and cortical regions. According to these investigators, Al is capable of extracting phosphate from root cells and other tissues of the plant in addition to preventing uptake of P from external sources.

Black (1968) explained, in part, the Al-P interaction in plant nutrition on the basis that Al and P interact to form a sparingly soluble salt. If one component is high the other will be reduced to low concentration by precipitation. Munns (1965b) verified qualitatively the above principle. He found that the Al concentration in 0.01M $CaCl_2$ extracts and displaced soil solutions from acid soils was decreased upon addition of soluble phosphate salts.

This interaction becomes significant only at low pH values since at high pH values the solubility of Al is limited by Al hydroxide and hydroxy Al interlayers in clays (Black, 1968).

Although low P concentration in plant tops is one of the manifestations of Al toxicity, studies with plants grown in nutrient solutions show increases in P content of roots with addition of Al to nutrient solutions (Randall and Voss, 1963). The above finding suggests that the increased P concentration may be caused by Al-phosphate precipitation on or in the roots (Black, 1968) and may be detrimental to the absorption process (Foy and Brown, 1963).

Phosphorous concentration in roots is often increased substantially in the presence of exchangeable and soluble Al (Randall and Voss, 1963, Clarkson, 1966; Rios and Pearson, 1964). However, other investigators have found decreased P concentration in roots at high levels of Al (Foy and Brown, 1963, 1964).

Aluminum toxicity without P deficiency has been observed (Munns, 1965a, 1965b). Humphries and Truman (1964) obtained increased P in shoots of Monterey pine (Pinus radiata D. Don) in the presence of Al.

Munns (1965b) indicated that Al toxicity could be alleviated by adding chelating agents, such as EDTA (ethylenediaminetetraacetic acid), to the nutrient solution and DeKock and Mitchell (1957) reported that high levels of Al chelates are absorbed by tomatoes without Al toxicity symptoms.

A relationship between Al toxicity and Ca deficiency has been found by several investigators. Johnson and Jackson (1964) reported that Al reduced both the absorption and accumulation of Ca by wheat (*Triticum aestivum* L.). Clarkson (1971) observed that Al decreased both the Ca associated with the free space of barley roots and the rate at which Ca previously absorbed by cells moved outward across the plasma membrane. Patterson (1965) concluded that Al reduced Ca uptake by corn but did not appear to inhibit transport to plant tops. Reduction in Ca uptake of cotton seedling roots by 0.3 ppm Al in solution was found by Lance and Pearson (1969). Lee (1971b) also obtained decreased Ca absorption by potato plants in the presence of Al. Similar results have been reported by Rees and Sidrak (1961) for several plant species.

Sensitivity of plants to aluminum

There is a marked difference in plant response to Al.

Foy and Brown (1964) studied this problem in different plant species. They found that growth of mustard (Sinapis alba L.), barley (Hordeum vulgare L.), cotton, and turnips (Brassica rapa L.) was reduced by small quantities of Al, whereas buckwheat (Fagopyrum esculentum Moench.) and soybean (Glycine max L.) were quite tolerant. They attributed Al tolerance of buckwheat to its efficiency in absorbing P. Similar findings have been reported by Munns (1965b). Jones (1961) also associated plant tolerance to Al with capacity to absorb P. He suggested that organic compounds produced by plants may act as chelating agents for Al and, in this way, prevent the precipitation of Al and P normally expected at physiological pH values.

Munns (1965b) reported only slight Al toxicity symptoms in subterranean clover (Trifolium subterraneum L.) growing in nutrient solution containing 5.4 ppm Al, but alfalfa failed to grow at this Al concentration. Long and Foy (1970) studied the differential sensitivity of two barley and two snapbean (Phaseolus vulgaris L.) varieties to Al. They observed leaf rolling in Al-sensitive 'Kearney' barley grown on unlimed soil and attributed this condition to "Al-induced Ca deficiency." Similar Al-Ca interactions have been reported by Foy, Fleming, and Armiger (1969a) in soybeans. Foy, Fleming, and Gerloff (1972) found higher Ca uptake by an Al tolerant snapbean variety than an Al sensitive variety. Reduced Ca uptake appeared to be a good indicator of Al sensitivity in two snapbean varieties. On the other hand, Lee (1971b) suggested that the greater Al tolerance in some varieties of Irish potatoes is associated with the ability of plants to absorb Mg and K. Vose and Randall (1962) also found differences in susceptibility of ryegrass (Lolium rigidum Gand.) varieties to Al. They associated tolerance to Al with low root CEC. Clarkson (1966) found differences in the tolerance to excess Al by bentgrass (Agrostis L.) species. Differential sensitivity to Al by alfalfa clones was studied by Ouellette and Desaureaux (1958). They found that plants which transported less Al to the tops were more tolerant of high exchangeable and soluble Al. The resistant clones also were able to accumulate higher amounts of soluble Ca in the roots.

Plants have differential affect on pH of nutrient solutions and this may explain in part the variable sensitivity to Al. These pH alterations depend on the relative rates of uptake of anions and cations. If the plant takes up a larger equivalent of cations than anions, the pH of the nutrient solution surrounding it decreases. Conversely, if it absorbs a larger equivalent of anions than cations the pH increases (Jackson and Adams, 1963; Kirby, 1968). The pH increase is generally accompanied by an accumulation of HCO_3^- in the nutrient solution (Riley and Barber, 1969).

Differential changes in soil pH by plants growing in soil have also been observed. Foy *et al.* (1965) found differential tolerance of Al by two wheat (*Triticum aestivum* L.) varieties. They attributed this phenomenon, at least in part, to plant-induced changes in pH around the roots, which presumably promoted precipitation of Al in the soil instead of the roots. In this study, the tolerant 'Atlas" variety raised the pH of the soil solution, while the sensitive 'Monon' decreased pH. Foy *et al.* (1967) also reached similar conclusions when growing wheat and barley varieties. Differential sensitivity to Al excess between cotton and peanuts (*Arachis hypogea* L.) in acid subsoils and nutrient solution was explained by Adams and Pearson (1970) as the result of differential changes in pH. Cotton roots created a more acid environment than did peanuts. Riley and Barber (1969) found accumulation of HCO_3^-, and an increase in pH at the root-soil interface environment of the soybean. The magnitude of HCO_3^- accumulation and pH increase was related to the NO_3^- concentration of the soil solution. They (1969) attributed this phenomenon to a greater uptake of anions than cations by the plant. Similar findings have been reported by Dodge and Hiatt (1972).

Increase in the concentration of Ca in the rhizosphere of soybean plants has been observed by Riley and Barber (1969, 1970). Barber and Ozanne (1970) found Ca accumulation in the rhizosphere of ryegrass, subterranean clover, and capeweed Arctotheca calendula (L.) Levyns. Conversely, lupine (Lupinis digitatus Forsk.) caused Ca depletion in the rhizosphere.

Differential Ca accumulation in the rhizosphere of plants caused by variable Ca absorption may explain variable sensitivity to Al excess under certain conditions. Differential Al tolerance between "Perry" and 'Chief' soybean varieties (Foy et al., 1969a) and 'Dade' and "Romano" snapbean varieties (Foy et al., 1972) did not appear to be associated with differences in pH changes in nutrient solutions.

Foy et al. (1974) reported variable sensitivity of sunflower genotypes to Al in acid soil and in nutrient solution. The greater acid soil sensitivity of one genotype was associated with chlorosis of young leaves, the stem of this genotype accumulated higher concentrations of Zn than those of more tolerant genotypes. Fertilization of unlimed soil with Mo reduced chlorosis but did not increase growth. Reid (1971) concluded that Al tolerance in certain winter barley populations was controlled by a single dominant gene.

Effect of manganese

Although Mn is an essential plant nutrient, in this review we are concerned only with the toxic effects of excessive Mn on plant development.

Manganese is generally considered to be one of the more common toxic metals in acid soils (Adams and Pearson, 1967). It is known that available Mn occurs in naturally acid soils in sufficient quantities to be toxic to plants (Adams and Wear, 1957; Neenan, 1960).

Adams and Wear (1957) found that Mn toxicity in cotton was more closely related to water-soluble than to exchangeable or reducible forms of Mn in the soil.

According to Hewitt (1963), Mn toxicity in plants is manifested in at least two ways: Mn-induced Fe chlorosis and a direct effect of the Mn ion. Although Mn toxicity symptoms vary with severity and the plant species involved, Hewitt made the following description of the symptoms: "Generally, roots take on a brownish coloration and older leaves are mottled. In some cases, dark-brown or dark, necrotic areas appear along petioles and leaf veins. There is often a white or yellow-green chlorosis of the leaf margin. Some plants show a pronounced marginal cupping of the leaves due to restricted marginal growth.' Manganese toxicity symptoms have also been described by Jackson (1967) and Black (1968). Sherman (1957) described Mn toxicity symptoms in pineapple (*Ananas comosus* Linn Merr).

Relatively low Mn concentrations in nutrient solutions may produce toxicity symptoms. According to Morris and Pierre (1949) as little as 1 to 4 ppm Mn in the solution may depress the yields of Lespedeza (*Lespedeza striata* Thunb), soybeans, and barley. White (1970) reported Mn toxicity symptoms when Mn concentrations in the tissue were approximately 1,000 ppm in beans, 550 ppm in peas, and 200 ppm in barley.

Lohnis (1951) stated that Mn toxicity symptoms usually develop when the Mn concentration in oven-dry leaves exceeds 1,200 ppm. He also observed that plants grown in warm greenhouses remained healthy when their Mn content exceeded that which produced toxicity in plants grown under field conditions. The influence of climatic conditions on the effect of Mn toxicity in plants was studied by Sutton and Hallsworth (1958). They found that increasing Mn supplies had relatively little effect on alfalfa growth when light intensity was low. However, at high light intensities, there was a marked decrease in growth with high Mn supply. Moreover, the toxicity symptoms were changed from the typical orange-brown necrotic spotting of Mn excess to a chlorotic pattern which resembled Mn-induced Fe deficiency.

Contrary to findings by Lohnis (1951), Williams and Vlamis (1957) noted that barley plants grown under the warmer greenhouse conditions had less tolerance to high Mn supplies than when grown under cooler temperatures. Manganese toxicity is a very important problem in acid soils that have been steamed since steaming causes an unusually high concentration of soluble and exchangeable Mn (Black, 1968). Therefore, pH control on steamed soils is extremely important.

Differential plant sensitivity to high Mn has been reported. Jackson (1967) listed plant sensitivity to excess Mn in the following order: Brassica crops > barley > potato > oat (Avena sativa L.) > sugar beet (Beta vulgaris L.).

However, alfalfa, cabbage (Brassica oleracea var. capitata) cauliflower (Brassica oleracea L.), cereals, sugar beet, and tomato were regarded as especially sensitive to Mn excess by Wallace (1951) and Sherman (1957).

Differences in sensitivity of cotton varieties to excess Mn have been reported by Foy, Fleming, and Armiger (1969b). They associated higher Mn tolerance with the capacity of plants to tolerate high Mn concentration in the top, rather than with reduced Mn uptake. However, Ouellette and Dessureaux (1958) reported that Mn tolerance is associated with reduced Mn uptake and/or transport to plant tops. Dessureaux and Ouellette (1958) concluded that tolerance of alfalfa to excess Mn is genetically controlled.

Effect of soil acidity on nutrient availability

Soil acidity may be responsible for both specific and nonspecific effects on nutrient availability. Reduction of root growth in acid subsoils layers is possibly the most important nonspecific effect of acidity on nutrient availability (Black, 1968). If pH values of nutrient solutions are low enough, there is no absorption of cations and those previously absorbed tend to diffuse from plants into the solutions. This may be caused by a competitive effect of K^+ and damage to the uptake mechanism (Black, 1968). It is possible that K^+ tends to displace Ca from the cell membrane where it plays an important role in maintaining the integrity of absorption and selection mechanisms involved in the uptake of cations (Black, 1968). Arnon and Johnson (1942) showed that the concentration of Ca required to obtain maximum yield of lettuce in culture solution increased with decreasing solution pH.

Reduction in Mo availability under acid conditions may be an important cause of poor growth on acid soils (Kamprath, 1972). Kamprath (1967) reported occurrence of Mg deficiencies in sandy soils where the pH was 5.0 or less and the exchangeable Al was relatively high. Decrease in Mg and K concentrations in the tops of some plants caused by high levels of Al in the substrate have been reported by Harward et al. (1955) and by Rees and Sidrak (1961).

Since Al toxicity affects root growth and reduces the absorption area of the plant, excess Al would be expected to reduce uptake of most nutrients regardless of interactions.

Effect of acidity on activity of soil microorganisms

As the soil becomes more acid the dominant microbial population generally shifts from bacteria and actinomycetes to fungi. Increase in rate of organic matter decomposition by liming has been observed in greenhouse experiments in which CO_2 evolution and N mineralization were measured, indicating that liming increases microbial activity. Liming a strongly acid peat soil in the Netherlands decreased the percent organic matter and increased N availability to crops (Mulder, 1950).

The evolution of CO_2 and mineralization of N and P in mineral soils were studied by Thompson, Black, and Zoellner (1954). Increasing pH from 5.2, however, did not increase CO_2 evolution. Similarly, N mineralization did not increase with pH On the other hand, these investigators found increases in P mineralization by liming. Similar findings have been reported by Halstead, Lapensee, and Ivarson (1963) in Canada. Threefold increase in sulfate production by decreasing acidity was observed by Nelson (1964) when the soil pH was increased from 4.0 to 5.0.

Autotrophic bacteria responsible for oxidation of NH_4^+ to NO_2^- and NO_3^- are quite sensitive to high acidity;

therefore, mineralization of organic matter in acid soils usually results in higher proportion of NH_4^+ than NO_3^-. This has been demonstrated by Cornfield (1952) in an investigation of 19 soils with varying acidity levels. Ammonium tended to accumulate in more acid soils, while NO_3^- accumulated in the less acid soils. Sensitivity of nitrifying bacteria to acidity was observed in pure culture by Aleem and Alexander (1960) and in soils by Morrill and Dawson (1962). Aleem and Alexander (1960) reported optimum growth of Nitrobacter sp. in pure culture at pH 8.0, while Morrill and Dawson (1962) observed optimum pH value of 7.0 for Nitrosomonas in soils.

Nitrification also takes place in acid soils. Weber and Gainey (1962) reported NO_3^- production in soil at pH values from 4.0 to 4.7 but they were unable to obtain nitrification in solution culture at pH below 6.0. The rate of NH_4^+ oxidation in acid soils depends on the N source which is applied. However, differences between sources are not as marked when soil reaction is near neutrality (Eno and Blue, 1954, 1957, Anderson and Purvis, 1955).

High amounts of NH_4^+ may be toxic to Nitrobacter under alkaline conditions resulting in significant accumulation of NO_2^- (Alees and Alexander, 1960) which may also be toxic to plants.

Nonsymbiotic N fixation by Azotobacter is affected by soil reaction. Azotobacter will grow at pH values below 6.0 if supplied with inorganic combined forms of N such as NH_4^+, but little or no N is fixed under these conditions (Black, 1968).

Symbiotic N fixation is also adversely affected by soil acidity; although there is variation among bacterial strains in their tolerance to low pH values, alfalfa strains are more sensitive to acid conditions than clover strains (Jackson, 1967). Munns (1965) found that N fixation was the first critically limiting factor for alfalfa growth as soil became moderately acid. Liming is often required for establishment of leguminous crops on acid soils (Jackson, 1967). The direct effect of H^+ concentrations appears to be more crucial for rhizobia than it is for higher plants. Vose and Jones (1963) found that amounts of Mn which were toxic to plants depressed the number and total volume of nodules on three varieties of white clover (Trifolium repens L.) The problem was diminished by increasing Ca supply. A discussion of the effects of liming on soil biological components was presented by Hubbell (1971).

Lime response on tropical soils

Interesting reviews on soil acidity and liming have been made by McLean (1971) and Kamprath (1971). McLean (1971) discussed the potentially beneficial effects from liming temperate and tropical acid soils, emphasizing chemical and physical soil properties likely to be affected by application of lime. On the other hand, Kamprath (1971) reviewed the potentially detrimental effects from liming highly weathered soils to neutrality.

Differential responses from liming tropical soils have been reported. The responses range from detrimental to a marked increase in yields. These seemingly conflicting responses are generally attributed to differences in soil types, plant species, and lime rates used. A review of plant response to liming acid soils in various tropical regions follows:

Brazil. "Campo Cerrado" soils represent about one-sixth of total Brazilian land area or approximately 150 x 10^6 ha (Alvim, 1952). Hardy (1960) stated that these soils are old (70 x 10^6 years), very deep (20 m), and that they resemble Ultisols and Mollisols. Alvim and Araujo (1952) reported pH values of "Campo Cerrado" soils ranging from 4.3 to 4.6 and base saturation between 13 and 18%. A substantial amount of research work on liming "Campo Cerrado" soils has been conducted. Mikkelsen, de Freitas, and McClung (1963) obtained increases in production of seed cotton, corn, and soybeans by liming three acid soils (pH 4.9), two Latosols and a Regosol. Cotton was the most responsive, corn was intermediate, and the soybean was least responsive. de Freitas _et al_. (1960) obtained increased corn yields by liming acid soils, pH less than 5.0, with high exchangeable Al saturation.

Colombia. On acid soils derived from volcanic ash, Parra (1969) reported increased yields of corn and sugarcane (_Saccharum officinarum_ L.) with the application of 2,000 kg/ha of $CaCO_3$. There was a lime x P interaction in corn. This author also reported increases in yields of beans (_Phaseolus_ sp.) and peanuts with lime rates up to 2,000 kg/ha. However, he obtained reduction in yields of beans and peanuts by lime rates higher than 4,000 kg/ha. On the other hand, Parra (1969) reported no effect of lime on growth of an established micaygrass [_Axonopus micay_ (Plugge) Hitch.] sod.

Lotero _et al_. (1971) reviewed research on liming in different regions of Colombia. Part of their review is summarized here by regions and experiment stations.

A. Antioquia. 'La Selva' (Agr. Exp. Sta.). Increases in dry forage of bahia (*Paspalum notatum* Flugge) and alfombra [*Axonopus compressus* (Swartz) Beauv.] grasses, and some "pega pega' (*Desmodium*) species were obtained with the application of 4 tons/ha of lime to an acid soil (pH 4.8 and exchangeable Al 2.1 meq/100 g of soil).

'Tulio Ospina Center'. Oven-dry forage yields of elephantgrass (*Pennisetum purpureum* Schumach.) were increased by 3.3 tons/ha/harvest with the application of 2 tons/ha of lime to a moderately acid red soil (pH 5.5); forage yields of Pangola were increased by 1.57 tons/ha/harvest. On the other hand, there was a slight decrease in forage yields of imperial [*Axonopus scoparius* (Flugge) Hitch.] and guinea (*Panicum maximum* Jacq.) grasses with liming.

"El Nus" (Agr. Exp. Sta.). On a red, acid soil, pH 4.9 and exchangeable Al of 0.45 meq/100 g of soil, forage yields of jaraguagrass (puntero) [*Hyparrhenia rufa* (Nees) Staph.] were slightly decreased with the application of 2 and 4 tons/ha of lime. The authors concluded that for this soil, an application of lime at a rate of 2 tons/ha is required for good establishment and growth of kudzu (*Pueraria phaseoloides* Bent) and "pega-pega "

B. Valle. "Jamundi": Application of $CaCO_3$ at 5 tons/ha to an acid soil increased dry matter yields of five grass species. The order of response of the grasses to lime application was as follows. elephant > braquiaria (*Brachiaria decumbens* Stapf.) > para [*Brachiaria mutica* (Forsk.) Staph] > Pangola > jaragua. The reviewers concluded that the results obtained were in agreement with those obtained in other areas, indicating that jaragua and Pangola grasses show a certain degree of tolerance to slightly acidic conditions.

C. Piedmont Llanero and Eastern Llanos. "La Libertad," Villavicencio. On a sandy loam soil, pH 4.7 and exchangeable Al of 2.8 meq/100 g of soil, the application of 4 tons/ha of lime increased oven-dry forage yields of braquiaria by 1.7 tons/ha/harvest. No additional increase in yields was obtained with the application of 8 tons/ha. In another experiment, lime at 4 tons/ha produced a marked increase in yields of elephant, micay, and jaragua grasses; there was a slight increase in yield of guineagrass and slight decrease in forage yields of Pangola, gordura (*Melinis minutiflora* Beauv.), and imperial grasses. The authors stated that in "La Libertad," lime and fertilizer are required for the establishment of the legume species calopo (*Calopogonium* *mucunoides* Desv) kudzu, "pega-pega," and crotalaria (*Crotalaria juncea* L.).

"Campoalegre," Villavicencio· Very slight increase in yields or no response to the application of 2 or 4 tons/ha of lime was obtained with jaragua and gordura grasses However, braquiaria yields were increased by application of 2 tons/ha

"Iraca," San Martin: Forage yields of jaragua and guinea grasses were increased by the application of 2 tons/ha of lime, while maximum yields of gorduragrass were obtained by applying 4 tons/ha. Yields of braquiaria were increased by this lime rate.

"El Pinal" farm, Orocue: Forage yields of jaragua, gordura, braquiaria, paja peluda (*Trachypogon plumosus* Nees.) and guaratara [*Axonopus purpusii* (Mez.) Chase] were increased by the application of 2 tons/ha of lime. No additional benefit was obtained with the application of 4 tons/ha.

In general, it appears that 2 tons/ha of lime are required for most grasses on soils from the eastern Llanos of Colombia.

Guyana. Cheaney (1972) did not obtain any response by *Digitaria setivalva* Stent to the application of 1,120 kg/ha of lime on a highly leached sandy loam with pH 5.3.

Costa Rica. Bornemisza, Laroche, and Fassbender (1967) obtained increased dry weight of tomato with the application of $CaCO_3$ at 12 meq/100 g of soil on a reddish-brown Latosol. Yields decreased slightly with the application of 36 meq/100 g of soil. The original soil pH in water was 4.5 and increased to 5.4 and 6.9 as lime applied increased from 12 to 36 meq/100 g of soil, respectively.

Decrease in herbage and root growth of Pangola was obtained by Lucas and Blue (1973) with application of 2,500 and 5,000 ppm $CaCO_3$ to Entisols from eastern Costa Rica in greenhouse experiments. Soil pH increased from 5.1 to 6.6 after application of 75 ppm P as triple superphosphate and 2,000 ppm Ca as $CaCO_3$.

Guatemala. Burgos[1] studied the effect of exchangeable Al on plant growth on three acid Latosols from the Izabal region, Atlantic Coast. He obtained reduction in yields of millet (*Setaria italica* L.) from two soils, San Felipe

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[1] Burgos, C. F. 1962 Studies on exchangeable aluminum in three tropical soils. MS Thesis. Soil Science Department, Univ of Florida, Gainesville, Florida 32611 (Unpublished data).

(pH 5.2 and 30 ppm exchangeable Al) and Ensenada (pH 5.6 and 30 ppm exchangeable Al) and a very small increase from Icacal soil (pH 4.6 and over 300 ppm exchangeable Al) by liming at 12.5 tons/ha of $CaCO_3$. He stated that lime apparently had little effect when used on these tropical Latosols. A more pronounced effect of lime might have been obtained with lower rates at least in the Icacal soil which contained high concentration of exchangeable Al.

Belize. (British Honduras). Hortenstine and Blue (1968) obtained increased oven-dry herbage yields of sorghum (*Sorghum vulgare* Pers.), tomato, and Pangola by liming a "Puletan" loamy fine sand soil at 1,000 ppm CaO in a greenhouse experiment. Calcium oxide rates of 2,000 ppm tended to decrease yields of all plant species. The soil pH increased from 5.4 to 6.3 and 7.3 as CaO was increased from 0 to 1,000 to 2,000 ppm.

Puerto Rico. Increased yields of several crops by lime have been obtained on this Island. Bonnet *et al.* (1945) obtained increased yields of velvet beans (*Stizolobium deeringianum* L.) after liming; while Pennock (1950) attributed increased yields of pineapple to lime. Similarly, Lugo-Lopez, Hernandez-Medina, and Acevedo (1953) obtained positive response of sugarcane to lime applications

Lime increased yields and protein content of kudzu growing in association with molassesgrass (*Melinis minutiflora* Beauv.) (Caro-Costas and Vicente-Chandler, 1963). Yields of heavily fertilized elephantgrass (Napiergrass) were doubled by liming (Abruna, Vicente-Chandler, and Pearson, 1964). Similarly, Abruna and co-workers (1965) obtained a large positive response of intensively managed coffee (*Coffea arabica* L.) to lime application on acid soils high in Mn. No response was obtained on acid soils low in Mn even though exchangeable Al was high. These results may have been associated with Al tolerance by coffee plants. The effect of lime application on tobacco growth (*Nicotiana tabacum* L.) was studied by Abruna-Rodriguez *et al.* (1970). They obtained approximately a sevenfold increase in tobacco yields by liming an acid soil from approximately 20 to 60% base saturation. Yields increased with increase in pH from 4.0 to 5.5 and decreased as exchangeable Al increased from about 10 to 40% saturation. In another experiment these authors obtained more than a twofold increase in tobacco yields when base saturation of a soil with very small amounts of exchangeable Al was increased from 35 to 60%. This response appeared related to decreased Mn toxicity since Mn concentration in the tobacco leaves decreased from about 2,000 to 500 ppm. Landrau, Samuels, and Rodriguez (1953) obtained increased yields of a kudzu-grass mixture by liming fertilized soil; in another experiment they obtained increased kudzu yields by liming, only on unfertilized soil. This differential response may have been related to the amount of exchangeable Al. Phosphorus in the fertilizer may have combined with Al to reduce its toxicity, but in the first instance, Al may have remained in sufficient concentration to cause toxicity until lime was applied.

Abruna and Vicente-Chandler (1967) obtained increased yields of heavily fertilized sugarcane growing on an acid Ultisol. Yields were increased from 1 to 47 tons/ha/year Abruna et al. (1974b) stated that the Oxisols in Puerto Rico rarely contain much exchangeable Al but can have rather high contents of exchangeable and easily reducible Mn. Conversely, Ultisols in Puerto Rico, are seldom high in exchangeable or easily reducible Mn but are high in exchangeable Al when acid. These authors (1974b) obtained an increase in corn yields when Oxisols were limed from pH values of approximately 4.0 to approximately 5.2. On an Ultisol, corn yields were increased statistically by increasing soil pH from about 4.5 to 5.3. They concluded that maximum corn and bean yields on these soils can be obtained by liming to about pH 5.2 or to approximately 70% base saturation based on CEC as determined with neutral 1N NH_4OAc. Increased yields of green beans (Phaseolus sp.) were obtained by Abruna and co-workers (1974a) by liming five Ultisols and one Oxisol. They also recommended liming these soils to pH 5.2 or to 70% base saturation as measured with neutral 1N NH_4OAc.

Hawaii. Rixon and Sherman (1962) reported that volcanic ash soils along the "Hamakua" and "Hilo" coasts have low pH values and high Al contents. Sugarcane grown on these soils has shown Ca deficiency. The authors reported increased growth and vigor of sugarcane with lime applications up to 11,000 kg/ha.

Monteith and Sherman (1963) obtained increased yields of sudangrass (Sorghum sudanese Stapf) with the application of 5,600 kg/ha of lime or calcium silicate to a Hydrol Humic Latosol (Akaka) but these treatments slightly decreased yields of sudangrass growing on a Humic Ferruginous Latosol (Puhi). Lime at 22,000 kg/ha tended to decrease yields on the Akaka soil and significantly depressed yields in the Puhi soil. Calcium silicate at 22,000 kg/ha increased yields on both soils. Akaka soil had a pH of 4.5 without lime and it increased to 5.5 and 7.0 as lime rates increased to 5,600 and 22,000 kg/ha, respectively, these rates of calcium silicate increased Akaka soil pH to 4.9 and 5.4. The pH of the Puhi soil which was initially 4.5 was increased to 5.9 and 7.4 with 5,600 and 22,000 kg/ha of $CaCO_3$ and 4.9 and 5.9 with the same quantities of calcium silicate.

Matsusaka and Sherman (1964) reported depressed growth and a chlorotic condition of pineapple following lime application, possibly associated with Fe deficiency. They also attributed reduced yields of sugarcane to liming.

Ceylon Ponnamperuma (1960) obtained pronounced increase in yields of rice with the application of 7.4 and 14.8 tons/ha of slaked lime ($Ca(OH)_2$) to a lateritic soil with pH 4.4 and 1,250 ppm free Fe_2O_3. Application of 22 tons/ha increased yields over the control but the increase was less than for 7.4 and 14.8 tons/ha. Ponnamperuma stated that the increase in yields by lime application to acid lateritic lowland rice soils may be attributed to:

1. decrease in concentration of ferrous iron in the soil solution,

2. decrease in the concentration of organic acids formed during the anaerobic decomposition of organic matter;

3. decrease in CO_2 concentration
4. increase in supply of Ca and Mg;
5. increase in supply of N and P; and
6. increase in availability of SiO_2.

India. Mandal and co-workers (1966) obtained differential response of several crops to the application of 4,000 kg/ha of lime to a red loam soil with a pH of 5.3. They grouped crops according to their response to lime as high, medium, and low. In the high group were rahar (Cajanus cajan L.), soybean, and cotton; while masur (Lens esculentum L.), pea (Pisum sativum L.), peanuts, corn, jowar (Andropogon sorghum L.), and wheat were in the medium group; and barley, marua (Elusine corcana L.), gondhi (Panicum miliare L.), rice, and castor bean (Ricinus comunis L.) were in the low group. Sinha et al., quoted by Mandal and collaborators, obtained increased corn yields with the application of 2,700 kg/ha of market lime (42% CaO) to a soil with a pH of 5.7.

Africa. Reeve and Sumner (1970) investigated lime requirements of Oxisols from Natal, South Africa. In general, maximum yields of trudan (Sorghum sudanense L.) were obtained with the application of 1/6 the lime required to increase soil pH to 6.5, as measured by the SMP buffer. Lime rates for maximum response varied, according to the soil used, from 1 to 4 tons/ha and were in good agreement with the amounts of $CaCO_3$ required to reduce the exchangeable Al index to 0.2 meq/100 g of soil.

Nye (1952) recorded only 15 positive growth responses to lime in 200 trials in soils with pH values ranging from 5.5 to 7.5 with several crops. The application of 4.9 tons/ha of lime to sandy soils at pH 4.8 did not appreciably increase yields of Rhodesgrass (Chloris gayana L.) at Entebbe, Uganda (Ledger, 1950). In Kenya, wheat did not respond to lime at pH values higher than 5.0 (Ignatieff and Lemos, 1963). Whyte, Moir, and Cooper (1968) concluded that the application of lime had no benefit in improving the establishment and productivity of grass pastures in areas with long dry seasons in Kenya and Southern Rhodesia.

Micronutrients in Soils and Plant Nutrition

Modern technology and higher rates of fertilizers have resulted in increased yields. However, more highly refined fertilizer materials have contributed to the widespread need for addition of micronutrients to soils. The availabilities of micronutrients to plants are affected by several factors, such as adsorption reactions with layer aluminosilicate and hydrous oxide minerals, complex formation with organic matter, and metal chelates. The above micronutrient interactions are controlled, to a degree, by soil reaction

Layer Aluminosilicate Minerals

Hodgson (1963) stated that the predominant reactions of heavy metals with soils and clay minerals involve surface adsorption. According to Mitchell (1964) and Ellis and Knezek (1972) most biologically important micronutrient cations are very readily adsorbed on the exchange sites of clay minerals and are difficult to displace. The apparent CEC of a clay was higher when determined for elements such as Zn^{2+}, Cu^{2+}, or Fe^{3+} which form weak bases, indicating that these elements may form basic salts with the clay in which only part of the valency goes to the exchange complex (Mitchell, 1964). On solubilization by weathering, B and Mo probably form complex anions which may be adsorbed by anion exchange (Mitchell, 1964).

Hodgson (1963) and Ellis and Knezek (1972) stated that heavy metals are held by clay minerals and organic matter in the exchange complex by coulombic forces, but the interaction of Cu and Zn with organic matter and clay mineral surfaces involve additional forces of attraction. Similar results were previously reported by Peech (1941) who found that a fraction of Cu and Zn added to soils could not be recovered by NH_4OAc extraction and that retention of Zn against neutral salt extraction was pH-dependent. Brown (1950) stated that a large portion of Zn added could be recovered immediately after addition to the soil, but that with time a larger fraction became nonextractable.

Elgabaly and Jenny (1943) found that a portion of Zn added to montmorillonite could not be extracted with neutral salts. A large portion of the nonexchangeable Zn was extractable with acid. The portion that was not extracted by acid was assumed fixed in the crystal structure. Similarly, Bingham, Page, and Sims (1964) reported that montmorillonite is capable of adsorbing Zn or Cu beyond its CEC, especially at near neutral or alkaline soil reaction.

Reddy and Perkins (1974) studied fixation of Zn by clay minerals. They found that bentonite and illite fixed significant quantities of Zn under wetting and drying. Fixation was directly related to pH. Kaolinite fixed relatively small amounts of Zn. These investigators concluded that Zn was fixed as a result of precipitation, physical entrapment in clay wedge zones and/or strong adsorption at the exchange sites. Furthermore, Zn fixation caused a reduction in CEC of the clay.

Ellis and Knezek (1972) stated that many of the micronutrients are retained by specific adsorption through covalent bonding to certain functional groups on clay surfaces. They also reported that Zn, Cu, and Fe enter into the crystal lattice of layer silicates through substitution. Hodgson (1963) suggested that diffusion of micronutrients into the relatively open crystal structure of layer silicates could account for their adsorption by clay minerals. McBride and Mortland (1974) studied the interaction of Cu^{2+} with montmorillonite using infrared, electron spin resonance, and other means. They concluded that dehydration of exchangeable Cu^{2+} allows these ions to become embedded in hexagonal cavities of the silicate structure, or penetrate into the empty octahedral positions and lower the layer charge. Resolvation allows the Cu^{2+} to move out of the hexagonal holes. Moreover, Cu^{2+} that has migrated to the octahedral layer is not exchangeable. These investigators did not find evidence for specific adsorption of Cu by montmorillonite.

Philipson (1953) suggested three possible mechanisms for the chemical combination of B with soils: anion exchange, chemical precipitation, and complex formation with acid groups in clays. Biggar and Fireman (1960) reported that B can be adsorbed on clay mineral surfaces Boron adsorption by soils can be described by the Langmuir adsorption isotherm (Hodgson, 1963). Harder (1961) concluded that B can be fixed in the crystal lattice of clays. He suggested that B substitutes for Al or Si in the tetrahedral position of illite.

Hydrous Oxide Minerals

Hodgson (1963) stated that under conditions of satisfactory aeration, Fe and Mn are bound in most soils mainly as precipitates of oxides and phosphates. Moreover, the movement and availability of these elements are governed principally by the way their oxides respond to changes in pH, oxidation potential, and the presence of soluble complexing agents. Ellis and Knezek (1972) suggested that in well aerated soils, Fe and Al oxides, hydroxides, and phosphates should be of major importance in controlling the level of these micronutrients in solution and their availability to plants. Jenne, quoted by Lindsay (1972a), stated that hydrous Mn and Fe oxides furnish the principal matrix into which less abundant heavy metals may be adsorbed, co-precipitated, or occluded. However, hydrous Al oxides are also important soil constituents controlling solubility of nutrients, especially in soils from the tropics. Lindsay (1972a) reported that solubility of Fe in soils is largely controlled by the solubility of hydrous Fe^{3+} oxides. Hodgson (1963) indicated that Fe oxides are not precipitated in solution as individual particles but exist as surface coatings on clay minerals. The strength of adsorption of Mo on Fe oxides decreases with increasing pH. In his review of "Trace Elements in Soils," Mitchell (1964) stated that a linear correlation between Mo and Fe extracted from German soils using different oxalate concentrations as extractants suggested that Mo is bound largely in the Fe rich material attacked by oxalate. Jones (1956, 1957) believed that the strength of Mo adsorption by soil minerals was as follows: hydrous Fe^{3+} oxide $>$ Al oxide $>$ halloysite $>$ nontronite $>$ kaolinite. Removal of Fe oxides markedly reduced Mo retention by the soil. Re (1957) suggested that molybdate ions replace surface hydroxyl groups on the hydrous oxide film. Hodgson (1963) believed that the pH sensitivity of the Mo-Fe oxide reaction is due to anion exchange of the molybdate ion with surface hydroxyls.

Marinho and Igue (1972) studied Zn absorption by corn growing on volcanic ash soils from Costa Rica. They found that the amount of Zn extracted with 0.01M Na_2-EDTA and $0.1\underline{N}$ HCl decreased as the free sesquioxide (R_2O_3) content increased. Furthermore, Zn uptake by corn plants decreased as free R_2O_3 in the soil increased. Similarly, Stanton and Burger (1967) observed decreased Zn absorption by Japanese millet (*Echinochloa frumentacea* L.) when phosphate and Fe oxides were present in the solution. Moreover, when P was absent, Zn absorption by millet plants was not affected by free R_2O_3, and the effect of P was negligible in the absence of free R_2O_3.

Sims and Bingham (1968b) showed that B retention by kaolinite and montmorillonite was largely caused by the presence of Fe and Al hydrous oxides, either as coatings on silicate mineral particles or as interlayer materials. These investigators (1968a) also demonstrated that hydrous Fe and Al were capable of B retention, the hydroxy Al forms exhibited a greater B retention capacity than the hydroxy Fe forms. Harada and Tamai (1968) stated that in Japan, B deficiency symptoms are frequently observed in crops growing on volcanic ash soils. In B adsorption experiments, these investigators found that the amounts of adsorbed B were relatively larger in volcanic ash than in other soils. Furthermore, B adsorption was closely related to free Fe and Al oxides. Bingham et al. (1971) found that B adsorption by amorphous soils from Mexico and Hawaii was closely related to amorphous SiO_2 plus Al_2O_3 and amorphous Al_2O_3.

Organic Matter

Soil organic matter forms stable complexes with metal ions. Organic compounds involved in binding micronutrients include humic and fulvic acids, and many individual biochemical substances, such as low molecular weight organic acids, polyphenols, amino acids, peptides, proteins, and polysaccharides (Stevenson and Ardakani, 1972). The metal ions bound to humic acids usually occur as insoluble forms. Conversely, soluble metals are mainly those associated with fulvic acids and with individual low molecular weight organic molecules (Stevenson and Ardakani, 1972). Mitchell (1964) indicated that SH groups produce very stable Cu complexes, that Cu is adsorbed as $CuOH^+$ by carbonyl groups and as Cu^{2+} by phenyl groups, and that NH_2 groups may also be involved in chelation. He stated that the optimum pH for complex formation of Cu with humic acids is 2.5 to 3.5, and pH 6.0 for complex formation with fulvic acid.

Hodgson (1963) suggested three systems to describe the association of organic matter and heavy metals: (1) immobilization of metals associated with immobile high molecular weight compounds, such as lignins, (2) soluble organic compounds when unassociated which form insoluble salts when combined with heavy metals, such as phytin salts of Fe and Al; and (3) association of heavy metals with short-chain organic acids and bases which appear to increase the solubility and movement of the metal. Schnitzer (1969a, b) found that two types of reactions participated in interactions of metal with fulvic acid. The most important reaction involved both phenolic-OH and acidic-COOH groups a reaction of lesser importance included less acidic COOH groups only.

Hodgson, Lindsay, and Trierweiler (1966) and Geering, Hodgson, and Sdano (1969) found that from 98 to 99% of the Cu, 84 to 99% of the Mn, and up to 75% of the Zn in displaced soil solutions occur in organic complexes. Differences in susceptibilities of plant species to micronutrient deficiencies have frequently been attributed to variation in production of organic acids (Hodgson, 1963).

The presence of organically complexed Mo, available to plants in some soils with moderate organic matter contents, is suggested by high Mo uptake by plants under relatively acid conditions (Mitchell, 1964). Increased availability of Mn to plants by addition of organic matter has been reported by Fujimoto and Sherman (1948) and Christensen et al. (1950). According to Kononova (1966) the increased plant growth frequently observed upon addition of humic substances may be due, at least in part, to increased uptake of bound micronutrients.

Copper is generally found in the deficient range in organic soils (Hodgson, 1963). Ennis (1962) found that carboxyl and hydroxyl groups were responsible for retention of 90% of the Cu added to peat soils. He suggested that the more tenaciously bound Cu in his experiments may have formed complexes with amino groups. There is also evidence that sulfide groups produce very stable Cu complexes (Mitchell, 1964; Ennis, 1962). Hodgson et al (1966) found strong complexing of Cu by soil organic matter. They believed that this is an important factor explaining why Cu deficiencies are not as prevalent as Zn deficiencies on soils with high pH, even though both cations show similar decreases in solubility with increase in pH. Davies, Cheshire, and Graham-Bryce (1969) reported that the strength of binding of low levels of Cu by humic acid increased as concentration of Cu decreased

Organic matter appears to interact with Zn in two important ways. Soluble Zn can be mineralized and made available to plants, or Zn can be bound into organic constituents that are immobile in soils and constitute a fixation mechanism by which Zn is not readily released (Lindsay, 1972b). Hodgson and co-workers (1966) demonstrated the presence of soluble Zn-organic matter complexes.

Hodgson (1963) suggested that H is probably associated with organic matter. He indicated that H may require metabolic processes to become incorporated into many of the organic forms with which it is associated.

Metal Chelates

Lindsay (1972b) reported that chelating agents increase the concentration of metals in soil solution. Similarly Norvell (1972), in his review on "Equilibria of Metal Chelates in Soil Solution," stated that the primary importance of soluble metal chelates in soils arises from their capacity to increase the solubility of added and native metal cations. The increased solubility and mobility of chelated metals have major effects on many aspects of soil chemistry, fertility, and plant nutrition. In addition to their role as carrier for micronutrients, chelating agents are frequently used in diagnostic extractions for available or labile nutrients and they are used for the selective fractionation of soil mineral phases (Norvell, 1972). Lindsay, Hodgson, and Norvell (1967) stated that chelating agents are expected to influence the availability of micronutrient cations in soils by increasing their diffusion rates.

Understanding stability diagrams of metal chelates in soil will contribute to the understanding of the simultaneous equilibria of chelating agents and metal ions in soils, selection of chelating ligands as micronutrient metal sources, and estimation of potential hazards from chelation of heavy metals by chelating agents added to soils in fertilizers or in effluents from waste treatment systems (Norvell, 1972). Calculations of chelate equilibrium also help in understanding the competition between chelating agents and plants for the uptake of Zn (Lindsay and Norvell, 1969) and other micronutrients.

The solubility of Zn is determined by the extent to which chelating agents combine with it (Lindsay, 1972b). This is also true for other metal cations. Chelating ligands can increase the movement of Zn both through convection and through diffusion (Lindsay, 1972b). In nutrient solutions, chelating agents often have a detrimental effect on Zn uptake. DeKock and Mitchell (1957) reported that Zn uptake by mustard plants was reduced by the addition of diethylenetriaminepentaacetic acid (DTPA) to nutrient solutions at pH 5.5. Similarly, Guinn and Joham (1962) showed that addition of ethylenediaminetetraacetic acid (EDTA) and hydroxyethylethylenediaminetriacetic acid (HEDTA) to nutrient solutions at pH 6.0, substantially reduced Zn concentration in cotton plants. Soil pH is very important in determining whether chelating ligands will increase or decrease availability of metal ions. According to Lindsay (1972b), Halvorson grew corn plants in nutrient solutions with 1.54uM Zn and either EDTA or DTPA as Fe source. Growth was normal when the pH was maintained at 5.0, but at pH 7.5 DTPA caused severe Zn deficiency.

Stevenson and Ardakani (1972) stated that at any one time, the quantity of micronutrients available to plants is affected not only by the production and destruction of chelating substances, but also by transformations carried out by microorganisms.

Soil Reaction and Liming

The solubility and availability of micronutrients is largely controlled by soil reaction. Charts relating nutrient availability to soil pH have been published and reproduced in many textbooks. Availabilities of B, Cu, Fe, Mn, and Zn are greater in acid soils and are decreased by increasing soil pH. On the other hand, Mo is the only micronutrient that becomes more available with increasing pH (Russell, 1961; Black, 1968; Hodgson, 1963). According to Hodgson (1963), the effect of pH is greater on the availabilities of Mn, B, and Mo than on Cu, Zn, and Fe.

Although Mn has positive valences of 7, 6, 4, 3, and 2, only the last three oxidation states are important in soils (Adams, 1965). Manganese in soils can be found mainly in five forms: (1) in the clay mineral structure, (2) as insoluble oxides of Mn^{3+} and Mn^{4+}, (3) complexed by organic matter, (4) exchangeable Mn^{2+}, and (5) Mn^{2+} in the soil solution (Mitchell, 1964; Hewitt, 1963). Several factors control the availability of Mn to plants; however, soil reaction is the single most important factor (Hodgson, 1963, Page, 1962). Christensen, Toth and Bear (1950) reported a decrease in exchangeable Mn of approximately 95% by liming a soil high in total and exchangeable Mn from pH 4.6 to 6.5. Tisdale and Bertramson (1949) reported that an alkaline or near alkaline condition of the soil is associated with Mn deficiency. Similarly, Sauchelli (1969) stated that liming strongly acid soils to an alkaline reaction is a common cause of Mn deficiency, and recommended liming acid soils to pH values of 5.7 to 6.0. Truog (1948) also found that high lime rates decreased available Mn. Similarly Russell (1961) stated that Mn deficiency typically occurs on calcareous soil or newly limed peats, although it can also occur on some neutral sandy soils and light loams.

Kamprath (1971) reported Mn deficiencies when soils low in Mn content (pH 5.0 or less) were limed above pH 6.2. In acid, sandy soils of Florida, the addition of lime reduces Mn availability and absorption by plants. However, this is not likely to induce Mn deficiency except when the native supply is very low (Fiskell, 1957). Forsee (1954) reported that organic soils from the Everglades in Florida, showed progressively decreasing amounts of available Mn as soil pH increased to 6.0. Other investigators have found reduction in the concentration and availability of Mn to plants with increase in pH (Cox and Reid, 1964; Fujimoto and Sherman, 1948; Lohnis, 1951; Monneret and Wilcox, 1969; White, 1970, Sutton and Hallsworth, 1958, and Vlamis and Williams, 1962).

According to Truog (1948), soil reaction influences Fe availability in much the same way as it does Mn.

Reduction in Fe availability by increase in soil pH is mainly a result of formation of insoluble oxides. Olsen (1950) showed that a $FeSO_4$ solution was oxidized upon passing through a soil column. The rate of oxidation followed a sigmoid-shaped curve, commonly found in biological systems. However, Hodgson (1963) stated that in most soils biological activity is not necessary to account for the formation of Fe oxides. Lindsay (1972a) reported that soluble inorganic Fe^{3+} reaches a minimum in the pH range of 6.5 to 8.0.

The solubility of Zn is highly pH-dependent. It loses 99% of its solubility with each unit increase in pH. The predominant Zn species below pH 7.7 is Zn^{2+} and above this pH the neutral species $Zn(OH)_2$ predominates (Lindsay, 1972a). Lime-induced Zn deficiency in acid soils can be explained by the pH-dependent relationship. Bandyopadhya and Adhikari (1968) studied the relationship between pH and extractable Cu, Mn, and Zn in alluvial soils of West Bengal. They found a significant negative correlation between pH and extractable Zn, and between pH and exchangeable and water soluble Mn. No significant correlations between pH and extractable Cu, and between pH and reducible Mn contents were obtained. Powers and Pang (1947) showed that Zn availability is lower in soils having a basic reaction than in acid or neutral soils. Similarly, Camp (1945) stated that the availability of Zn declines as the pH of soil increases. He reported that the critical point is between 5.5 and 6.5. Russell (1966) found adequate availability of Zn for *Phaseolus lathyroides* L. up to pH 6.0 to 6.3, but further increase in pH reduced Zn concentration in the plant to deficiency levels. Seatz (1960) stated that lime applications increased the intensity of Zn deficiency. Truog (1948) reported that Zn deficiencies are very common on calcareous soils which reduce solubility and availability of Zn. Similarly, Lindsay (1972b) stated that the solubility of Zn decreases with increase in soil pH. therefore, a greater incidence of Zn deficiency would be expected in calcareous soils. This had been demonstrated by Navrot and Ravikovitch (1969) who found that Zn deficiencies were more common in calcareous soils than in other mineral soils.

Lindsay (1972a) reported that below pH 7.3, Cu^{2+} predominates, while above this pH, $CuOH^+$ is most abundant. Bryan (1940) found that Cu deficiency was common in citrus growing on acid soils in Florida. Similarly, Rodriguez-Gomez and Blue (1974) observed Cu deficiency symptoms in Pensacola bahiagrass plants growing on an acid sandy soil. Harmer (1941) reported that muck soils from Michigan gave a greater response to Cu application when the pH was below 6.0. Riceman and Donald (1939), and Teakle and Stewart (1939) obtained response to Cu applications on very acid muck soils as well as on calcareous soils. Truog (1948) stated that Cu deficiencies sometimes occur on calcareous soils. Hodgson (1963) reported that uptake of Cu by plants is only slightly influenced by pH. He reported that the amounts of Cu and Zn extracted with chemical solvents vary more with soil pH than the amounts removed by plants.

Ellis and Knezek (1972) stated that B is thought to exist as undissociated H_3BO_3 or as an anion in soil solution. They reported that at relatively low concentrations (less than 0.1M) H_3BO_3 dissociates and hydrates to form $B(OH)_4^-$, which should be essentially the only ionic species present. Only above pH 9.2 does H_2BO_3 become dominant (Lindsay, 1972a). Most B fertilizers are of the form $B_4O_7^{2-}$ and are expected to hydrolyze to H_3BO_3 (Sillen and Martell, 1964 and Hingston, 1964).

Sims and Bingham (1968a) found that B adsorption by soils is increased with increasing pH up to about 9.0. Hodgson (1963) stated that adsorption of B by hydrated Fe^{3+} oxide, kaolinite, and other clay minerals increases as pH rises.

The concentration of MoO_4^{2-} increases 100-fold with each unit increase in pH. The increased solubility of Mo with liming can be explained on the basis of the solubility of Fe^{3+} molybdates (Lindsay, 1972a).

Plant Response to Micronutrients in Tropical Soils

According to Drosdoff (1972) micronutrient deficiencies are seldom a limiting factor in crop production under traditional systems of agriculture in the humid tropics. However, with the increase in crop yields by the use of modern technology, the need to supply one or more micronutrients has become evident

A considerable number of investigations have been conducted with micronutrients on 'Campo Cerrado" soils in Brazil. Igue and Gallo (1960) reported Zn deficiency in a commercial corn planting on a sandy loam soil (pH 5.2) that had been fertilized with N and P. McClung and coworkers (1958) conducted preliminary greenhouse fertility studies on 'Campo Cerrado' soils and found that Pangola-grass growth was limited by nutrients in the following order: P > micronutrients > N > Ca and Mg > K. Growth without P was the same as in the control pots. When micronutrients were omitted, forage yields were reduced by

74% of those obtained with complete fertilization. No effect was obtained by adding K. Meuer, Ludwick, and Kussow (1971) used 0.1*N* HCl for extracting Zn from three Oxisols and one Alfisol. Zinc concentrations ranged from 1.3 to 2.2 ppm. These investigators found in greenhouse experiments that liming to pH 5.5 did not affect Zn uptake by plants. But liming a soil with 1.5 ppm extractable Zn to pH 6.5 caused Zn deficiency symptoms in plants. Liming to pH 7.4 produced deficiency symptoms in plants growing on all soils.

On "Campo Cerrado" soils, McClung *et al.* (1961) obtained an increase in cotton yields with the application of B and Mo. deFreitas, McClung, and Lott (1960) obtained a positive growth response by soybean to Zn and Mo applications, but corn yields were increased only by Zn application. Rushel, Brito and Carvalho (1969) coated seeds of soybeans with rock phosphate containing B, Mo, or Zn. They found that coating seeds with rock phosphate containing Mo was an effective means of supplying this nutrient.

According to Cox (1972) and Drosdoff (1972), Mo deficiencies are usually restricted to weathered acid soils. McClung *et al.* (1961) obtained a positive growth response of cotton to applications of B in limed and unlimed "Campo

Cerrado" soils. Molybdenum application increased yields only in unlimed soils.

Mikkelsen et al. (1963) obtained increased yields of seed cotton and corn with the simultaneous application of Zn, Mo, and B. Individual effects of micronutrients were not evaluated. These authors stated that B deficiencies frequently occur on light-textured sandy soils in humid regions because of loss of the element in drainage waters. Zinc deficiencies are related to the low levels of native Zn present in this soil. They (1963) concluded that both B and Zn availabilities are reduced by liming "Campo Cerrado" soils.

Medcalf and co-workers (1955) conducted preliminary experiments with micronutrients on sandy loam soils in Brazil. Coffee production was increased with the application of 31 kg/ha of several chelated compounds of Cu, Fe, Mn, or Zn. The authors concluded that the response was probably from increased Fe availability since mild symptoms of Fe deficiency were observed in untreated plots. However, Zn may have been a factor in increasing production since its concentration in oven-dry leaf tissue was 10.7 ppm, which may be below the critical concentration. Medcalf and Lott (1956) observed that although both Fe and Zn deficiencies may occur in coffee in Brazil, Fe deficiency symptoms have been more widespread than those for Zn. These investigators (1956) reported increased coffee yields of 240% by the application of metal chelates. Cox (1972) reviewed the literature on micronutrients in tropical Latin America. He concluded that Zn response in "Campo Cerrado" soils has generally been obtained when the Zn concentrations in corn and soybean leaves were less than 20 and 23 ppm, respectively.

Boron deficiency seems to be widespread in plants growing in volcanic ash soils. These soils appear to fix B, making it unavailable to plants. Boron deficiencies in coffee, bananas, and cacao growing on volcanic ash soils from Ecuador were reported by Tollenaar (1966). He (1969b) also observed B deficiencies in sugarcane and oil palm (Elaeis guineensis Jacq.) growing on volcanic ash soils.

In Chile, Schalscha et al. (1968) investigated the availability of Zn, Cu, Fe, and Mn in volcanic ash soils using various extractants. They concluded that the soils studied contained sufficient quantities of available Cu, Zn, and Fe. On the other hand, they considered a potential Mn deficiency in these soils. Tollenaar (1969a) reported that severe growth disorders in pine trees in central

Chile (trees appeared bushy and stunted due to repeated dieback of the shoots) were eliminated and growth was increased with the application of 25 g borax per tree.

Silvey and Carlisle (1971) investigated the effect of lime and Zn applications on growth and nutrient concentration of hairy indigo (*Indigofera hirsuta* L.) on clay soil near Santa Fe, Panama. Liming increased forage yields but decreased extractable Zn and P. On the other hand, Zn application increased forage Zn concentration, but it did not affect any other soil or plant response.

Igue and Marinho (1972) studied Zn absorption by corn growing on volcanic ash soil from the "Meseta Central" in Costa Rica. They found an inverse relationship between R_2O_3 content of the soil and Zn absorption by corn plants, and between R_2O_3 content and Zn extracted by 0.01M Na_2-EDTA. Zinc application increased corn yields and Zn concentration in the plant tissue.

In Honduras, Khangoo and Karon (1961) obtained increased banana yields with the application of Mo as ammonium molybdate to soils ranging in texture from sandy loam to sandy clay loam and with pH values varying from 4.5 to 6.0.

Flores and Mayagoitia (1959) determined water soluble

B in Mexico. Concentrations ranged from 0.3 to 3.0 ppm B and were considered sufficient for normal plant growth.

In Puerto Rico, Landrau and Samuels (1956) summarized results of investigations on lime and micronutrient applications. They reported a widespread occurrence of Fe chlorosis in pineapple. Yields of sweet potato (Ipomoea batatas L.) were increased with the application of B (33.6 kg/ha borax) to a sandy clay soil. Soil and spray applications of Zn sulfate eliminated Zn deficiency symptoms in grapefruit (Citrus sp.) trees. Silva and Vicente-Chandler (1974) obtained increased plantain yields with the application of 62 kg/ha of borax (11% B) to a typical Ultisol in the humid mountains of Puerto Rico. No additional increase in yield was obtained with higher B rates. Similarly, Hernandez and Lopez (1969) obtained increase in plantain yields on Lares clay (Ultisol) with foliar application of Zn and Fe sprays.

In Hawaii, Kanehiro and Sherman (1967) obtained an increase in corn yields with the application of 16 kg/ha of Zn to a silty clay soil (Ultisol). Zinc concentration in the oven-dry corn plant increased from 26.3 to 38.3 ppm in the control and 16-kg/ha Zn treatments, respectively. Kanehiro and Sherman (1967) considered the critical level of 0.1N HCl extractable soil Zn to be between 1 and 2 ppm in their study.

MATERIALS AND METHODS

Study Area

Soil samples were collected in August and September 1972. Four sites were selected in Costa Rica (Fig. 1) and four in the Eastern Llanos of Colombia (Fig. 2). Surface soil samples for greenhouse experiments, laboratory trials, and analytical determinations were taken at depth of 0 to 18 cm. Profile samples were also collected from these sites. Soils were bagged and shipped by air freight to Miami. They were fumigated with methyl bromide at the USDA Quarantine Station, Miami. Upon arrival at Gainesville the soils were screened, air-dried, and stored. Hereafter, soils collected at sites 1 through 4 from Costa Rica will be referred to as San Vito, San Isidro, Grecia, and Alajuela; and sites 5 through 8 from Colombia as Agronomy Area, Carimagua, Drainageway, and East Carimagua, respectively.

Temperatures and rainfall for four stations in Costa Rica are shown in Table 1. Data for Alajuela are not provided; however, climate in this area is expected to be

Table 1--Temperatures and rainfall for four stations in Costa Rica

		Month												
		Jan	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann.
		San Vito* (1.000 m elevation)												
Temperature	Min.	21	21	21	22	22	21	21	21	21	21	21	21	21
(C)	Max.	23	23	25	24	23	23	23	23	22	22	22	23	23
Rainfall	Avg.	182	69	139	261	387	346	328	523	517	615	481	102	3.950
		San Isidro+ (744 m elevation)												
Temperature	Min	17	17	18	18	19	18	18	18	18	18	18	17	18
(C)	Max.	28	29	30	30	28	27	27	28	28	27	27	28	28
Rainfall	Avg.	18	16	34	122	289	314	306	359	376	472	309	72	2,687
		Grecia‡ (1,018 m elevation)												
Temperature	Min.	16	16	17	17	18	18	17	17	17	17	17	16	17
(C)	Max.	28	29	30	30	29	28	28	29	28	27	28	27	28
Rainfall	Avg.	5	5	12	44	318	370	168	285	481	421	166	51	2,326
		San Jose§ (1,172 m elevation)												
Temperature	Min.	14	14	15	15	16	16	16	16	15	15	15	15	15
(C)	Max.	24	26	27	27	27	27	26	26	27	26	25	25	26
Rainfall	Avg.	11	4	13	44	222	269	213	240	325	332	149	46	1,863

*Temperature for 1 year, rainfall for 3 years

+Ten years

‡Seventeen years

§Ninety years

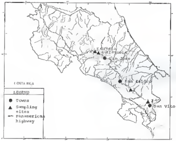

Fig. 1--Location of soil sampling sites in Costa Rica.

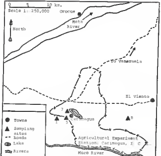

Fig. 2--Location of soil sampling sites in Colombia.

intermediate between that of Grecia and San Jose.

The eastern Llanos of Colombia are representative of tropical savanas. The area is located between 4 and 5° north latitude. The average annual maximum temperature is 28C and the mean annual rainfall at Orocue (Fig. 2) is approximately 1700 mm. The average monthly rainfall distribution is as follows: 12, 32, 65, 165, 180, 237, 205, 240, 165, 255, 145, and 33 mm from January through December, respectively. The mean relative humidity is 80% during the wet season and 50 to 60% for the dry period (FAO, 1965).

Laboratory Procedures

Analytical Determinations

Particle size distribution was determined by the Bouyoucos hydrometer method (Bouyoucos, 1962). Total elemental analyses were accomplished by treating 0.5 g of finely ground soil in platinum crucibles with 15 ml of 48% HF and 1.5 ml of 70% $HClO_4$ in three increments to remove Si. A similar procedure to the one outlined by Jackson (1958) was followed, except that he recommended decomposing 0.1 g of soil with 5 ml HF and 0.5 ml $HClO_4$. Soil pH was determined in 1:2 soil-water and 1:2 soil-1*N* KCl suspensions using a combined calomel-glass electrode and a

Corning Model 12 pH meter. Cation exchange capacities were determined by extraction with $1\underline{N}$ NH_4OAc at pH 4.8 and 7.0, and distillation of the adsorbed NH_4^+ after displacing it with Na^+ as described by Chapman (1965). The NH_4OAc extracts were used to determine exchangeable cations. Calcium, Mg, K, and P were extracted by $1\underline{N}$ NH_4OAc (pH 4.8) using 5 g of soil in 25 ml of extracting solution. The suspension was equilibrated for 30 minutes and filtered. Phosphorus was also extracted by the Bray 2 method ($0.03N$ NH_4F + $0.1\underline{N}$ HCl) of Bray and Kurtz (1945). Potassium and Na in all extracts, and Ca and Mg extracted by $1\underline{N}$ NH_4OAc (pH 4.8) equilibrated for 30 minutes were determined by flame emission in a Beckman (B or DU) spectrophotometer. Calcium and Mg in other soil extracts and solutions from plant ash were determined by atomic absorption spectrophotometry. Phosphorus extracted by $1\underline{N}$ NH_4OAc (pH 4.8) was determined by the ammonium molybdate-stannous chloride method (Jackson, 1958). Soil P removed by other extractants was determined by the ascorbic acid method described by Watanabe and Olsen (1965). In plant extracts, P was determined by the aminonaphtholsulfonic acid-reduced molybdophosphoric blue color method of Fiske and Subbarow (1925).

To determine P retention, 50 ml of a 50 ppm P solution were added to 1 g of soil. The suspension was shaken for 16 hours in a reciprocal shaker. Subsequently, four drops of saturated KCl solution were added to increase flocculation, the suspension was filtered through No. 42 Whatman filter paper. The amount of P retained was calculated from the difference between P concentration in the original solution and P concentration in the final filtrate. The procedure outlined by Bower and Wilcox (1965) was followed for preparing the soil saturation extracts for determining soil salinity. Electrical conductivities were determined by a salt-bridge.

Organic matter was assayed by the Walkley-Black wet oxidation method (Allison, 1965). Soil N was determined by the micro-Kjeldahl method, following the procedure described by Bremner (1965a). Nitrate was extracted by a saturated solution of $CaSO_4$ and determined colorimetrically by the phenoldisulfonic acid method (Bremner, 1965b). Sulfate was extracted with water (100 ml of deionized water were added to 20 g of soil). The suspension was shaken for 30 minutes in a reciprocal shaker; a few drops of saturated KCl were added to flocculate the colloids. The mixture was centrifuged for 5 minutes at 2,000 rpm, and filtered through No. 42 Whatman filter paper. Sulfate-S was determined gravimetrically with $BaCl_2 \cdot 2H_2O$ using the method outlined by Hanna (1964).

Exchangeable Al was removed by 1N KCl solution, following the procedure outlined by McLean (1965), it was determined by atomic absorption spectrophotometry. Soil Cu, Zn, Mn, and Fe were determined by extracting 10 g of soil with 50 ml of a 0.1N HCl solution. Samples were shaken for 30 minutes, centrifuged for 5 minutes at 2,000 rpm, and filtered through No. 42 Whatman filter paper. Atomic absorption spectrophotometry was used to determine the above micronutrients. Boron was extracted by the hot-water method described by Wear (1965) and determined by the curcumin method (Jackson, 1958), but the standard curves were prepared as indicated by Wear (1965).

Clay minerals were identified by X-ray diffraction. The method outlined by Whittig (1965) was followed for sample preparation. Amorphous soil materials were determined by differential solution as described by Jackson (1965). Free Fe and Al oxides were extracted by the citrate-dithionate method outlined by Mehra and Jackson (1960).

Lime Incubation

A lime incubation trial was conducted with each soil to determine amounts of $CaCO_3$ required to neutralize exchangeable Al and to measure subsequent changes in pH values. Finely ground, reagent grade $CaCO_3$ was applied at 0, 50, 100, 300, 400, 800, 1200 and 1600 ppm Ca. Two-hundred-gram soil samples were mixed with their appropriate lime treatment in double polyethelene bags. Enough distilled water was added to bring the moisture content approximately to field capacity. Soils were incubated for 7 weeks in closed bags. At the end of the incubation period, exchangeable Al was removed by 1N KCl and determined as indicated above. Soil pH was determined in water and in KCl as described previously.

Greenhouse Experiments

Three important warm-season grasses were used for greenhouse experiments. Pensacola bahiagrass (bahia) is a species native to Latin America and is extensively grown in the tropics and subtropics. It is an aggressive species and is tolerant of soil acidity.

Pangola digitgrass (Pangola) is very responsive to fertilization and has shown a certain degree of tolerance to moderately acidic conditions (Lotero et al., 1971; Rodriguez-Gomez and Blue, 1974). In 1967, there were over 400,000 ha planted to Pangola on the Gulf Coast in Mexico (Hodges et al., 1967). Caro-Costas, Vicente-Chandler, and Abruna (1972) stated that Pangola is the most widely used pasture grass in the humid mountain and coastal regions of Puerto Rico. Pangola is also important in other tropical and subtropical regions and its culture is expected to increase.

Pearl millet (millet) is also an important forage in some tropical and subtropical regions. Important characteristics such as salt tolerance and a degree of tolerance to drought conditions, make this a potentially important crop in many tropical regions.

Lime x Frit Experiment with Leon Fine Sand

A preliminary greenhouse experiment was conducted using the top 15 cm of Leon fine sand, an Aeric Haplaquod from Florida, to determine whether facilities were adequate for micronutrient investigations and to study the effect of lime and micronutrient frit 503 (FTE 503, Ferro Corporation, Cleveland, Ohio)[1] on growth and composition of Pangola, bahia, and millet grown in succession. Calcium carbonate was applied to supply 0, 200, 400, 800, and 1600 ppm Ca; and frit 503 (frit) was applied at 0 and 30 ppm. The soil was limed, moistened approximately to field capacity, and incubated in closed bags for 3 weeks. After the incubation period, 2 kg of soil were placed in plastic pots containing 1 kg of gravel previously washed with distilled water. Three Pangola sprigs (stolons), 10-12 cm long, were planted in each pot. Bahia and millet were grown from seeds. They were thinned to 3 bahia and 6 millet plants per pot. The experiment was a split-plot arranged in a randomized block design with four replications. A basal application of N, P, K, Mg, and S was made 1 week after the initial planting of Pangola. Subsequently, N and K were applied following each harvest. Phosphorus, Mg, and S were applied two times after their initial application. Three harvests of Pangola were obtained, followed by three harvests of bahia, each at 6-week intervals; millet followed and was harvested three times at 30-day intervals.

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[1] FTE 503 contains 18.0% Fe, 7.5% Mn, 7.0% Zn 3.0% Ce, 3.0% B, and 0.2% Mo

The initial soil and plant data indicated that plant growth might have been limited by Cu deficiency. To investigate this possibility, Cu treatments at rates of 0, 0.5, 1.0, and 2.0 ppm Cu as $CuSO_4.5H_2O$ were superimposed after the first bahia harvest on the treatments without frit.

Forage was dried, weighed, and prepared for determinations of P, K, Ca, Mg, Fe, Mn, Zn, and Cu. Soil samples for chemical analyses were taken before initial planting and after the last harvest.

Lime x Frit Experiment With Soils from Costa Rica and Colombia

This experiment was conducted to study the effect of four lime rates and two micronutrient frit levels on growth and chemical composition of millet and Pangola on eight soils, four from Costa Rica and four from Colombia. The SMP buffer method was used as the criterion for selecting lime rates. For each soil, lime was applied at 0, 1/3, 2/3, and 3/3 the theoretical amount of $CaCO_3$ required to bring soil pH to 6.4 (Table 2). Frit was applied at 0 and 30 ppm. Lime, frit, and sufficient distilled water to adjust the soil moisture approximately to field capacity were mixed with the soil in an electric rotary mixer and incubated in closed double polyethylene bags for 6 weeks. At the end of the incubation period 1 kg of soil was placed in plastic pots containing gravel, previously washed with distilled water. The pots were filled with soil to approximately 2 to 3 cm from the top. Millet seeds were planted on May 29, 1973. One week after seeding, plants were thinned to six per pot. The same procedure was followed for the second harvest. After the second millet

Table 2--Lime and phosphorus treatments used in the lime x frit experiment with soils from Costa Rica and Colombia

	Ca as $CaCO_3$				P as H_3PO_4
	ppm				
San Vito	0	960	1920	2880	400
San Isidro	0	760	1520	2280	300
Grecia	0	960	1920	2880	450
Alajuela	0	890	1790	2680	350
Agronomy Area	0	690	1390	2080	200
Cararao	0	890	1790	2680	250
Drainageway	0	1150	2290	3440	500
East Carimagua	0	160	320	480	60

cut, three Pangola stolons, 10-12 cm long, were planted in each pot. The experiment was a 4 x 2 factorial arranged in a randomized block design with four replications. A basal application of the following nutrients was made 3 days after millet seeds were planted initially: 100 ppm each of N and K as NH_4NO_3 and KCl, respectively; and 50 ppm Mg and 66 ppm S from $MgSO_4.7H_2O$ Phosphorus was applied as H_3PO_4 in amounts equivalent to 1/4 the P retention capacity of each soil (Table 2), as measured by the P sorption determination. Subsequently, 100 ppm N either as NH_4NO_3 + KNO_3, $NH_4H_2PO_4$, or NH_4NO_3 + KNO_3 + $Mg(NO_3)_2.6H_2O$; and 100 ppm K as KNO_3 or KH_2PO_4 were applied after each harvest. Very poor millet growth was observed for all treatments in East Carimagua soil after the first harvest. To determine whether P deficiency was the cause of reduced plant growth, 60 ppm P as H_3PO_4 were applied to two replications 1 week before the second millet harvest. After the second Pangola harvest, two replications of all soils received additional P at the same rates as at the beginning of the experiment, but $NH_4H_2PO_4$, KH_2PO_4, H_3PO_4, or combinations were the P sources. Magnesium and S at 50 and 66 ppm, respectively, as $MgSO_4.7H_2O$ were applied after the fifth and sixth harvests of Pangola. The same rate of

Mg as /$\overline{\ }$Mg$(NO_3)_2 \cdot 6H_2O$/$\overline{\ }$7 and additional P at the same rates as at the beginning of the experiment were applied after the seventh harvest. Distilled water was applied to each pot as required to keep plants turgid.

Two harvests of millet were obtained at 30-day intervals. These were followed by five harvests of Pangola from soils from Costa Rica and eight harvests from soils from Colombia, each at 6-week intervals. After each harvest, the fresh forage was cut with scissors into 1 to 3 cm pieces and the material was dried and weighed. Two grams of the dry forage were ashed at 450 to 500C. The ash was taken into solution in 5N HCl, dried on a hot plate and redissolved in HCl to give a final volume of 50 ml of 0.1N HCl. This solution was used for determinations of P, K, Ca, Mg, Mn, Zn, and Cu by the methods mentioned above.

Zinc x Copper Experiment

Soil analyses, initial plant analyses, and reddish-purple and chlorotic Pangola leaves indicated the possibility of Zn and/or Cu deficiencies in plants growing on Drainageway and East Carimagua soils without frit applied. An experiment was established to determine whether the above hypothesis was correct and to study the effect of applied

Zn and Cu on growth and chemical composition of Pangola, and on extractable soil micronutrients. Basal applications of $CaCO_3$ to provide 3,440 and 160 ppm of Ca were made to Drainageway and East Carimagua soils, respectively. The same procedure as in the previous experiments was followed for lime incorporation. Drainageway soil was incubated for 3.5 weeks before planting, while East Carimagua soil was planted 4 days after liming. Before filling the plastic pots with soil, gravel, previously washed with tap water, 1N HCl, tap water and distilled water, was placed in each pot. Planting procedure was similar to that followed for the previous experiment. Three weeks after planting, Zn and Cu were surface applied as sulfates. For Drainageway soil, Zn was applied at 0, 5, 10 and 20 ppm, and Cu at 0, 15, 30 and 60 ppm. East Carimagua soil received 0, 2.5, 5.0, and 10.0 ppm each of Zn and Cu as sulfates. The experiment was a 4 x 4 factorial arranged in a randomized block design with four replications. Two replications of the Drainageway soil were treated with 2 ppm B as H_3BO_3. A basal application of 100 ppm N as $NH_4H_2PO_4$ + $Mg(NO_3)2.6H_2O$; 200 ppm P as $NH_4H_2PO_4$ + KH_2PO_4; 100 ppm K as KH_2PO_4, 100 ppm Mg as combination of $MgSO_4.7H_2O$, $Mg(NO_3)_2.6H_2O$, and $MgOAc.4H_2O$· and 80 ppm S as $MgSO_4.7H_2O$,

$CuSO_4.5H_2O$, and $ZnSO_4.7H_2O$, or their combinations was applied to Drainageway soil. The materials above were varied depending on levels of Cu and Zn sulfates to provide equal quantities of N, P, K, and S to each treatment.

East Carimagua soil received the following basal treatment. 100 ppm N as KNO_3 + NH_4NO_3, 100 ppm K as KNO_3 + KH_2PO_4; 60 ppm P as KH_2PO_4; 100 ppm Mg as $MgSO_4$ - $7H_2O$ + MgOAc. $4H_2O$; and 50 ppm S as $MgSO_4$. $7H_2O$, $CuSO_4$ $5H_2O$, and Zn SO_4. $7H_2O$, or their combinations. These chemical compounds were varied as for the Drainageway soil to provide equal quantities of N, P, K, and S; different materials were used because rates of Cu and Zn sulfates were lower for the East Carimagua soil. Subsequently, 100 ppm N as $NH_4H_2PO_4$ + $Mg(NO_3)_2$. $6H_2O$ or KNO_3 + NH_4NO_3; and 100 ppm K as KH_2PO_4 or KNO_3 were applied to Drainageway soil. Two hundred parts per million P as KH_2PO_4 and $NH_4H_2PO_4$ were applied to this soil after the first harvest. East Carimagua soil received 100 ppm N as KNO_3 + $Mg(NO_3)_2.6H_2O$ + NH_4NO_3, 100 ppm K as KNO_3 + KH_2PO_4; 60 ppm P as KH_2PO_4 and 50 ppm Mg as $Mg(NO_3)_2$ $6H_2O$ after the first harvest. Both soils received 100 ppm N as KNO_3 + NH_4NO_3, and 100 ppm K as KNO_3 after the second harvest. Three harvests were obtained from each soil. The harvesting procedure and preparation of samples for determination of nutrients were similar to procedures followed for the previous experiment. Soil samples for micronutrient extractions and pH determinations were taken after the second harvest.

RESULTS AND DISCUSSION

Laboratory Studies

Physical and Chemical Characteristics of the Soils

Field descriptions of soil profiles from Costa Rica and their tentative classification into orders are shown in Appendix A, Table 38. All soils were classified as Ultisols, except San Isidro soil which was placed in the Oxisol order. Field estimates of texture of these soils varied from loam for San Vito, Grecia, and Alajuela to clay loam for San Isidro. Some physical and chemical characteristics of the profiles of soils from Costa Rica are shown in Table 3. Clay was the predominant particle size in these soils. In general, the clay content increased and other particle sizes decreased with depth below the surface horizon; however, the trend did not continue into the deeper horizons of all soils. There appeared to be a relationship between decreased pH and increased exchangeable Al with depth in the San Vito soil. A similar relationship was observed in the Grecia soil between pH measured in KCl

Table 3--Profile characteristics of soils from Costa Rica

Depth	Particle size distribution Sand	 Coarse silt	 Fine silt	 Clay	Textural class	pH H₂O	 KCl	Exch. Al
cm	------------	------	% ------	------------				ppm
				San Vito				
0-8	36	14	9	41	Clay	5.50	4.50	20
8-36	24	14	4	58	Clay	5.30	4.20	210
36-76	20	10	6	64	Clay	4.90	3.90	640
76-91	25	11	5	59	Clay	4.85	3.85	680
91-122	39	13	3	45	Clay	4.85	3.90	980
122-152	28	1	2	69	Clay	4.85	3.90	1.460
				San Isidro				
0-5	25	16	4	55	Clay	5.35	4.35	60
5-30	16	9	4	71	Clay	5.25	4.30	100
30-61	5	8	3	80	Clay	5.25	5.15	5
61-102	15	7	3	71	Clay	5.35	5.25	8
102-152	13	7	2	78	Clay	5.20	5.20	8
152-183	23	4	1	72	Clay	5.30	5.00	5
				Grecia				
0-36	30	25	6	35	Clay loam	5.20	4.45	70
36-91	16	11	8	65	Clay	4.95	3.85	320
91-183	19	15	5	61	Clay	5.05	3.90	370
183-213	20	21	5	54	Clay	5.25	3.80	300

Table 3 (Continued)

Depth	Particle size distribution				Textural class	pH		Exch. Al
	Sand	Coarse silt	Fine silt	Clay		H_2O	KCl	
cm	%							ppm
				Alajuala				
0-13	27	35	6	32	Clay loam	4.95	4.40	50
13-51	26	34	0	40	Clay loam	5.05	4.35	60
51-81	20	18	5	57	Clay	4.85	4.45	10
81-122	23	16	5	56	Clay	4.80	4.15	60
122-152	19	15	4	62	Clay	5.10	4.10	60

and exchangeable Al. In the San Isidro soil, pH measured in KCl increased and exchangeable Al decreased below the 30-cm depth. Exchangeable Al remained constant throughout the profile of the Alajuela soil, except for the 51 to 81-cm horizon, while pH measured in KCl tended to decrease with depth.

Field descriptions of the profiles and classification of soils from Colombia into orders are shown in Appendix A, Table 39. Agronomy Area and Drainageway soils were tentatively classified as Oxisols, while Cararao and East Carimagua soils were classified as Ultisols. Field estimates of texture for Agronomy Area, Cararao, Drainageway, and East Carimagua soils were clay loam, clay, loam to clay loam, and sandy loam, respectively. Characteristics of the profiles of these soils are shown in Table 4. In general, Colombian soils contained more silt and less clay than soils from Costa Rica. Generally, pH measured in KCl and exchangeable Al in soils from Colombia were more uniform throughout the profiles than in the soils from Costa Rica. This uniformity may be associated with more complete weathering of soil profiles from the eastern Llanos of Colombia than those from Costa Rica.

Field estimates of texture were presented, even though

Table 4--Profile characteristics of soils from Colombia

Depth	Particle size distribution				Textural class	pH		Exch. Al
	Sand	Coarse silt	Fine silt	Clay		H_2O	KCl	
cm	%							ppm
					Agronomy Area			
0-13	14	46	2	38	Silty clay loam	5.25	3.90	240
13-36	17	41	4	38	Silty clay loam	5.25	4.00	220
36-81	17	42	1	40	Silty clay loam	5.25	4.10	150
81-178	15	41	1	43	Silty clay	5.35	4.20	60
178-188	15	35	2	48	Clay	5.35	4.10	150
					Cararao			
0-10	14	32	4	50	Clay	5.00	3.75	380
10-46	13	43	6	38	Silty clay loam	4.85	3.85	220
46-107	21	24	4	51	Clay	4.80	3.75	500
107-183	37	12	5	46	Clay	4.65	3.80	480
					Drainageway			
0-20	28	26	7	39	Clay loam	4.05	4.00	230
20-76	50	13	4	33	Sandy clay loam	4.95	3.85	220
76-183	15	49	4	32	Silty clay loam	5.00	4.05	160
183-213	24	40	1	35	Clay loam	5.15	3.95	280
					East Carimagua			
0-13	66	23	3	8	Sandy loam	5.60	4.15	60
13-25	63	25	3	9	Sandy loam	5.65	4.15	60
25-107	56	26	3	15	Sandy loam	5.45	4.25	50
107-213	55	22	3	20	Sandy loam	5.25	4.20	50

some are at variance with laboratory data, because cementation of small particles can make fine textured soils behave as coarse textured soils under field conditions.

Total concentrations of selected elements in the soils sampled from Costa Rica and Colombia are shown in Table 5. The predominant elements determined were Al and Fe, while Cu and Zn were in lowest concentrations. In general, soils from Costa Rica, except the San Isidro soil, contained more total P, Ca, Mg, Al, and micronutrients than soils from Colombia. These characteristics may be an indication that soils from the eastern Llanos are more highly weathered. Potassium and Na were found in similar concentrations in all soils. Other properties of the soils are shown in Table 6. Soil pH values for soils from Costa Rica ranged from 5.2 to 5.3 when measured in water and from 4.3 to 4.5 when measured in KCl, while pH values of soils from Colombia ranged from 4.6 to 5.3 and from 3.8 to 4.3 when measured in water and KCl, respectively. Except for East Carimagua, soils from Colombia contained higher concentrations of 1$\underline{N}$ KCl exchangeable Al than soils from Costa Rica (Table 6). The Al saturation of soils from Costa Rica (using CEC measured at pH 4.8) ranged from 2.4 to 7.3%, while Al saturation of three soils from Colombia ranged

Table 5--Total analyses of soils from Costa Rica and Colombia

Soil	Concentrations of elements									
	P	K	Ca	Mg	Na	Al	Fe	Mn	Cu	Zn
	%							ppm		
San Vito	0.08	0.35	0.25	0.45	1.45	8.83	6.15	780	170	207
San Isidro	0.07	0.04	0.04	0.06	1.13	14.40 ✓	9.23	1,390	138	90
Grecia	0.11	0.24	0.20	0.32	1.18	11.70	9.00	1,220	195	112
Alajuela	0.12	0.24	0.21	0.39	1.45	10.63	8.63	1,065	200	114
Agronomy Area	0.03	0.20	0.03	0.06	1.30	6.15 ✓	3.05	53	30	26
Cararao	0.03	0.35	0.03	0.07	1.33	6.93	1.01	70	28	31
Drainageway	0.08	0.33	0.03	0.06	1.25	7.65	1.00	73	33	49
East Carimagua	0.01	0.05	0.02	0.02	1.30	2.70	2.13	28	28	15

Table 6--Chemical properties of soils from Costa Rica and Colombia

						Extractable nutrients*						
	pH		Exch.	CEC		NH4OAc (pH 4.8)				Bray 2	SO_4^{2-}	NO_3^-
Soil	H2O	KCl	Al	pH 4.8	pH 7.0	Ca	Mg	K	P	P	S	N
			meq/100 g						ppm			
San Vito	5.3	4.3	1.39	19.0	37.4	1.80	2.08	0.42	0.45	3.5	12	2.3
San Isidro	5.2	4.5	0.62	12.3	23.5	0.43	0.92	0.15	0.45	2.1	11	1.8
Grecia	5.2	4.4	1.04	14.6	38.5	0.25	0.92	0.51	0.45	1.6	14	1.4
Alajuela	5.3	4.5	0.40	16.4	38.1	0.80	0.83	1.08	0.45	3.3	21	7.1
Agronomy Area	4.8	3.9	3.19	7.8	15.5	0.08	0.18	0.14	0.20	2.5	3	1.3
Cararao	4.6	3.8	4.77	9.7	17.3	0.08	0.40	0.22	0.85	9.8	20	6.5
Drainageway	5.3	4.3	2.51	21.0	48.5	0.08	0.18	0.26	0.65	3.2	12	1.2
East Carimagua	5.0	4.2	0.89	2.2	4.3	Trace	0.18	0.08	0.45	2.3	14	1.1

*Sulfate-S was extracted with water and NO_3-N with a $CaSO_4$ solution.

Table 6 (Continued)

Soil	OM	N	C/N	EC	Retained P
	---- % ----			mmho/cm	ppm
San Vito	10.0	0.50	12	0.45	1.660
San Isidro	6.3	0.30	12	0.20	1.175
Grecia	11.3	0.36	18	0.26	1.820
Alajuela	10.0	0.43	14	0.28	1.430
Agronomy Area	4.5	0.16	17	0.15	735
Cararao	5.1	0.19	15	0.24	965
Drainageway	20.6	0.96	12	0.18	1,990
East Carimagua	1.7	0.06	16	0.24	250

from 40.5 to 49.2%. The Drainageway soil had an Al saturation of 12%. The difference in Al saturation between the Drainageway soil and the other three soils from Colombia was probably a result of the high organic matter content of this soil which imparted a higher CEC.

High pH-dependent CEC was observed in all soils since this value was almost doubled when determined at pH 7.0 as as compared to pH 4.8 (Table 6). This pH-dependent CEC is characteristic of soils occurring in the humid tropics that are dominated by colloids bearing a constant surface potential which is solely determined by the potential determining ions, H^+ and OH^- (Van Raij and Peech, 1972). Soils from the eastern Llanos of Colombia, except for Drainageway, had very low CEC when measured at pH 4.8- this was apparently related to the exchange characteristics of the inorganic colloidal material.

Ammonium acetate exchangeable cations are shown in Table 7. There was little effect of pH of the NH_4OAc on exchangeable Ca, Mg, K, and Na. However, exchangeable Al and Fe were considerably higher when determined by extraction with NH_4OAc (pH 4.8) than by NH_4OAc (pH 7.0). For some soils, the amounts of Al removed at pH 4.8 were higher than the CEC measured at the same pH, indicating

Table 7—Exchangeable cations in soils from Costa Rica and Colombia

	Ammonium acetate											
	pH 4.8						pH 7.0					
Soil	Ca	Mg	K	Na	Al	Fe	Ca	Mg	K	Na	Al	Fe
	meq/100 g											
San Vito	4.98	1.70	0.45	0.24	15.30	0.41	4.12	1.50	0.35	0.17	0.18	0.00
San Isidro	2.53	0.79	0.19	0.23	7.83	0.25	2.19	0.76	0.16	0.14	0.07	0.00
Gracia	1.39	0.96	0.57	0.20	17.68	0.27	1.13	0.89	0.49	0.13	0.15	0.00
Alajuela	3.62	1.39	1.50	0.14	11.24	0.20	3.12	1.06	1.40	0.12	0.07	0.00
Agronomy Area	0.30	0.12	0.14	0.13	6.88	0.24	0.30	0.13	0.12	0.13	0.07	0.00
Cararao	0.42	0.41	0.21	0.13	7.89	1.14	0.38	0.39	0.18	0.12	0.07	0.00
Drainageway	0.22	0.14	0.30	0.20	38.39	0.14	0.12	0.13	0.25	0.15	1.08	0.00
East Carimagua	0.11	0.04	0.05	0.12	2.84	0.14	0.11	0.04	0.06	0.14	0.07	0.00

that Al in excess of the exchangeable was removed. Soils from Costa Rica contained larger amounts of exchangeable Ca, Mg, and K than soils from Colombia (Table 7). Very small amounts of Ca were extracted from Colombian soils by 1N NH_4OAc (pH 4.8) in 30 minutes (Table 6). This extracting solution removed small amounts of P from all soils, and small amounts of Mg and K from Colombian soils. Bray 2 solution extracted more P from Cararao soil (9.8 ppm) than from any of the other soils. Phosphorus removed by Bray 2 solution from the other soils ranged from 1.6 ppm in Grecia to 3.5 ppm in San Vito. All soils retained large amounts of P, except for East Carimagua (Table 6). This is a known characteristic of soils containing large proportion of sesquioxides and amorphous materials such as allophane.

Electrical conductivities of saturation extracts did not exceed 0.32 mmhos/cm for any of the tropical soils studied (Table 6). At conductivities of 2 mmhos per cm or less in saturation extracts all plants would be expected to grow satisfactorily (Bower and Wilcox, 1965). Salinity problems would not be expected in any of the soils under consideration.

Low concentrations of SO_4-S and NO_3-N were found in all soils (Table 6). Only East Carimagua soil had low organic matter content. In the other soils organic matter concentration ranged from medium (4.5%) in the Agronomy Area soil to very high (20.6%) in the Drainageway soil (Table 6). Except for the Drainageway soil, soils from Colombia contained less total N than soils from Costa Rica (Table 5). The C/N ratios varied from 11.6 in San Vito to 18.3 in Grecia soil.

In general, kaolinite and amorphous materials (noncrystalline) were the main colloidal constituents of soils from Costa Rica (Table 8). Relatively high concentrations of free Fe oxides were also found in these soils. In addition, San Vito and Alajuela soils contained large amounts of gibbsite. Soils from Colombia contained kaolinite, Al-interlayered vermiculite, and very small amounts of gibbsite. The Colombian soils contained small amounts of amorphous material, except for the Drainageway soil.

Lime Incubation

The effect of selected rates of Ca as $CaCO_3$ on soil pH values and on 1N KCl exchangeable Al are shown in Table 9 for soils from Costa Rica and in Table 10 for soils from Colombia. Data for Ca rates higher than 800 ppm are not

Table 8--Predominant minerals, in the clay fraction, and oxides in soils from Costa Rica and Colombia

Soil	Kaolinite	Gibbsite	Vermiculite	Amorphous Materials	Free oxides	
					Fe	Al
	% of clay					
San Vito	13	16	-	27	10	4
San Isidro	24	4	-	20	16	4
Grecia	23	4	-	19	14	7
Alajuela	20	18	-	26	14	5
Agronomy Area	17	Trace	10-20	9	6	3
Cararan	13	Trace	10-20	8	2	1
Drainageway	3	Trace	10-20	38	1	5
East Carimagua	16	7	10-20	11	5	1

Table 9--Effect of incubation with lime on pH and 1N KCl exchangeable aluminum in soils from Costa Rica

Ca as $CaCO_3$	pH		Exch. Al
	H_2O	KCl	
ppm			ppm
	San Vito		
0	5.65	4.45	36
100	5.65	4.55	36
200	5.65	4.65	31
400	5.65	4.70	16
800	5.70	4.90	0
	San Isidro		
0	5.55	4.50	26
100	5.55	4.50	15
200	5.55	4.55	10
400	5.70	4.75	10
800	5.85	5.00	0
	Grecia		
0	5.35	4.40	68
100	5.35	4.45	42
200	5.40	4.50	31
400	5.45	4.60	21
800	5.60	4.80	10
	Alajuela		
0	5.25	4.40	57
100	5.25	4.40	42
200	5.25	4.45	31
400	5.35	4.55	21
800	5.35	4.75	10

Table 10--Effect of incubation with lime on pH and 1N KCl exchangeable aluminum in soils from Colombia

Ca as $CaCO_3$	pH		Exch. Al
	H_2O	KCl	
ppm			ppm
	Agronomy Area		
0	5.05	3.90	198
100	5.15	3.95	167
200	5.25	4.05	132
400	5.40	4.15	61
800	5.75	4.55	10
	Cararao		
0	4.80	3.80	274
100	4.85	3.90	243
200	4.95	4.00	183
400	5.05	4.00	132
800	5.35	4.25	36
	Drainageway		
0	5.35	4.35	230
100	5.35	4.45	100
200	5.35	4.45	73
400	5.45	4.60	68
800	5.55	4.80	26
	East Carimagua		
0	5.45	4.20	45
100	5.75	4.40	15
200	5.80	4.80	5
400	6.30	5.50	0
800	7.65	6.70	0

presented because exchangeable Al at higher rates was negligible. Incubation without lime decreased exchangeable Al and increased pH in water for soils from Costa Rica, except for the Alajuela soil (Tables 6 and 9). In this soil, pH tended to decrease and exchangeable Al tended to increase with incubation. Small amounts of Al were removed from the Costa Rican soils at Ca levels higher than 400 ppm. Soil pH in water was slightly increased by application of $CaCO_3$ to supply up to 800 ppm of Ca. A more pronounced effect of liming was observed on pH determined in 1N KCl. Soils from Colombia, except for East Carimagua, contained higher concentrations of exchangeable Al than soils from Costa Rica (Tables 9 and 10).

Increasing lime rates considerably increased pH of these soils, except for soil pH determined in H_2O in the Drainageway soil. Smaller changes in pH obtained by liming soils from Costa Rica and the Drainageway soil were associated with higher buffer capacities of these soils. Incubation without lime reduced exchangeable Al in all soils from Colombia. In general, 800 ppm Ca as $CaCO_3$ were required to reduce exchangeable Al to 36 ppm or less, except for East Carimagua soil which required only 200 ppm Ca to reduce exchangeable Al to 5 ppm.

Greenhouse Experiments

Lime x Frit Experiment with Leon Fine Sand

Results from this preliminary experiment with Leon fine sand (Aeric Haplaquod) have been published (Rodriguez-Gomez and Blue, 1974). Data in Table 11 show the effect of lime on some chemical properties of the soil. Soil pH in water and in 1N KCl increased by 2 and 3 units, respectively, as Ca applied was increased from 0 to 1,600 ppm. Exchangeable Al was reduced by one-half by the first lime increment. Equilibrium extractable Ca and P increased, and extractable Mg and exchangeable Al decreased with liming, while extractable K was not affected by application of $CaCO_3$. There was no apparent effect of frit on the soil properties mentioned above.

Concentrations of 0.1N HCl extractable micronutrients in unlimed soil before initial planting, with and without frit application, were as follows: Cu, 1.5 and 0.5; Zn, 3.2 and 1.0; Mn, 2.0 and 0.5; and Fe, 55 and 52 ppm, respectively. Generally, there was a slight decrease or no apparent effect of applied $CaCO_3$ on extractable micronutrients.

Applied frit increased oven-dry forage yields of Pangola and bahia at all lime rates but had no effect on

Table 11--Effect of lime on some chemical properties of Leon fine sand*

Ca as $CaCO_3$	pH		NH_4OAc(pH 4.8) extractable				Exch.
	H_2O	KCl	Ca	Mg	P	K	Al
ppm			ppm				
0	4.7	3.5	93	64	0.88	18	115
200	5.3	4.1	250	52	0.85	18	60
400	5.5	4.5	334	48	0.98	15	20
800	6.1	5.4	593	48	1.20	15	10
1600	6.7	6.5	1185	49	2.20	18	10

*Soil samples were taken after 3 weeks' incubation and before initial planting.

millet yields (Table 12; Fig. 3). Maximum yields of Pangola were obtained with the first lime increment when frit was applied. The highest lime rate significantly decreased yields of Pangola when compared with the maximum.

When no frit was added, oven-dry forage yields of bahia were increased by the first two lime increments. Very poor growth was obtained on unlimed soil and at the two highest rates when frit was omitted. Maximum oven-dry forage yields of bahia were obtained when frit was added regardless of lime rate. Oven-dry forage yields of millet increased through all rates of $CaCO_3$ and this species did not respond to frit (Table 12).

There was a positive response of bahia to Cu applications (Table 13). Forage yields were significantly increased by the first Cu increment but additional Cu did not increase yields further. Copper concentrations in bahia herbage increased from 1.4 ppm when no Cu was added to 3.4 ppm at the 2-ppm Cu rate. Oven-dry forage yields of millet were not affected by applied Cu. However, forage Cu increased from 2.7 to 7.5 ppm as applied Cu increased from 0 to 2 ppm.

The positive response of Pangola to the first lime

Table 12--Effect of calcium and micronutrients applied to Leon fine sand on oven-dry herbage yields*

Ca as $CaCO_3$ ppm	Pangola Frit 503 -	Pangola Frit 503 +	Bahia Frit 503 -	Bahia Frit 503 +	Millet Frit 503 -	Millet Frit 503 +
	g/pot					
0	8.4b[†]	15.3c	0.4c	29.8a	7.4d	5.6d
200	17.4a	25.9a	13.3a	30.9a	7.7d	8.6c
400	11.5b	21.7ab	8.0b	29.1a	11.8c	10.6b
800	10.3b	22.6ab	0.6c	32.0a	12.6b	12.7a
1600	2.6c	19.8bc	0.3c	33.0a	16.1a	13.4a

* Values are totals of two harvests for pangola, and three harvests for bahia and millet.

[†] Values within a column followed by different letters are significantly different at the 0.05 probability level.

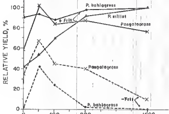


Fig. 3--Effect of lime and frit in Leon fine sand on relative herbage yields of the three grasses

Table 13--Effect of copper applied to Leon fine sand on yields and copper concentrations in bahia and millet

Cu applied	Herbage			
	Bahia		Millet	
	yield	Cu	yield	Cu
ppm	g/pot	ppm	g/pot	ppm
0.0	4.3b*	1.4c	11.0a	2.7c
0.5	10.0a	2.4b	10.4a	4.9b
1.0	12.0a	2.7ab	12.2a	5.7b
2.0	11.8a	3.4a	10.8a	7.5a

*Values within a column followed by different letters are significantly different at the 0.05 probability level.

increment was likely associated with reduced Al toxicity and/or Ca as a nutrient (Table 12). Leaf tips from unlimed soil were chlorotic, distorted, and became necrotic with time. These symptoms were similar to those described by Long and Foy (1970) as "Al-induced Ca deficiency." Without added micronutrients, Pangola forage Cu concentrations were less than 2 ppm (Fig. 4), indicating that Cu was also an important growth-limiting factor for this species.

It is probable that bahia is more tolerant of high exchangeable and soluble Al and/or low soil Ca than Pangola. For this reason, no effect of lime was observed when micronutrients were applied. Very low forage yields of bahia without frit were apparently caused by Cu deficiency and the response to the first lime increment may have been related to increased Cu availability, since forage Cu concentrations, without micronutrients, were higher at the first lime increment for the three grass species (Fig. 4). Pangola and bahia growth depression at higher lime rates, without frit, was likely caused by decreased Cu availability with increased soil pH. Response of bahia to Cu as $CuSO_4$, superimposed on treatments without frit, demonstrated that this element was the main growth-limiting factor. Because maximum bahia yields were obtained when

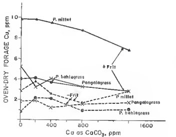


Fig. 4--Effect of lime and frit in Leon fine sand on copper concentrations in the forage of the three grasses.

forage Cu concentrations were between 2.4 and 2.7 ppm it appears that the critical Cu concentration for bahia is approximately 2.5 ppm.

Response of millet to lime may have been related to decreased exchangeable Al and/or higher Ca requirements. In unlimed soil, plants were cholorotic, younger leaves were rolled, and the growth point became necrotic. With the first lime increment, leaf shape appeared normal and the necrosis disappeared, but the plants remained light green in color. The chlorotic symptoms were not present in plants growing on soil treated with Ca rates higher than 200 ppm. For comparable treatments, forage Cu concentrations in millet were higher than in the other two species (Fig. 4). Higher Cu concentrations may explain why millet did not respond to either frit or Cu applications.

Nutrient concentrations in herbage from treatments which produced maximum growth of the three species (200 ppm applied Ca for Pangola and bahia, and 1600 ppm for millet) are given in Table 14. In general, Fe, Cu, and macronutrient concentrations were highest in millet, while Pangola forage had highest Mn and Zn concentrations. Without lime, Ca concentrations were the same in all species (Fig. 5). However, at the two highest lime rates, Ca concentrations in

Table 14--Nutrient concentrations in the three grasses grown on Leon fine sand*

Grasses	Oven-dry herbage nutrients							
	P	K	Ca	Mg	Fe	Mn	Zn	Cu
	--------	%	--------		----	ppm	----	
Pangola	0.39	1.98	0.22	0.35	58	65	46	3.2
Bahia	0.23	1.56	0.29	0.46	70	40	29	4.1
Millet	0.70	3.11	0.91	0.46	129	27	32	4.9

*Nutrient concentrations shown are for treatments where plants grew best. For Pangola and bahia the lime rate was 200 ppm, and for millet 1,600 ppm Ca as $CaCO_3$.

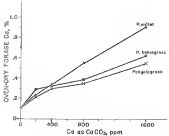


Fig. 5--Effect of lime in Leon fine sand on calcium concentrations in the forage of the three grasses.

millet herbage were higher than in the other two species. Forage Mn concentrations were decreased by increasing rates of $CaCO_3$ however, all Mn concentrations were above reported critical levels.

Lime x Frit Experiment with Soils from Costa Rica

This experiment was conducted to study the effect of four levels of lime and two of frit on growth and composition of millet and pangola and to relate their growth and composition to the effect of treatments on extractable micronutrients, 1N NH_4OAc (pH 4.8) extractable nutrients, pH, and exchangeable Al. Soil samples for analytical determinations were taken after incubation but before initial planting.

Chemical properties of the soils

pH of unlimed soils tended to increase with incubation (Tables 6 and 15). This was possibly related to increased NH_4OAc (pH 4.8) extractable Ca. At the highest lime rates, pH in water ranged from 6.0 in the Alajuela soil to 6.5 in San Vito and San Isidro soils, while in KCl, pH ranged from 5.6 in Grecia and Alajuela soils to 5.8 in San Isidro

Table 15--Effect of lime on some chemical properties of soils from Costa Rica*

Ca as $CaCO_3$	pH		Exch. Al	NH_4OAc (pH 4.8) extractable			
	H_2O	KCl		Ca	Mg	P	K
ppm			ppm	ppm	ppm	ppm	ppm
				San Vito			
0	5.6	4.5	20	415	156	0.85	145
960	5.8	4.9	5	1,090	140	0.45	145
1,920	6.1	5.3	0	2,000	135	0.45	148
2,880	6.5	5.7	0	2,650	110	0.45	142
				San Isidro			
0	5.7	4.6	20	265	88	0.45	62
760	5.9	5.0	0	760	76	0.20	64
1,520	6.1	5.3	0	1,425	76	0.45	68
2,280	6.5	5.8	0	1,950	72	0.45	62
				Gracia			
0	5.4	4.5	50	90	105	0.45	230
960	5.5	4.9	5	585	94	0.45	252
1,920	5.9	5.2	0	1,400	88	0.45	226
2,880	6.2	5.6	0	2,000	88	0.45	234
				Alajuela			
0	5.1	4.5	20	295	110	0.45	515
890	5.3	4.9	3	845	115	0.45	515
1,780	5.7	5.3	0	1,020	115	0.45	515
2,680	6.0	5.6	0	2,000	128	0.45	515

*Soil samples were taken after 6 weeks' incubation and before initial planting.

soil. Generally, extractable Mg decreased with lime, and P and K were unaffected.

Micronutrients were extracted with 0.1N HCl, except B which was removed by the hot-water method. Micronutrient concentrations in soils from Costa Rica are shown in Table 16. Copper concentrations in all unlimed soils were high, except for San Isidro which had 2.2 ppm, but this concentration appeared adequate for normal plant growth. In the preliminary experiment with Leon fine sand, soil Cu concentration of 1.5 ppm was adequate for Pangola and bahia grasses.

Zinc concentrations in untreated soils varied from 1.4 to 2.6 ppm for San Isidro and Alajuela soils, respectively. Similar ranges in Zn concentrations (1.3 to 2.2 ppm) have been reported by Meuer et al. (1971) for three Oxisols and one Alfisol in Brazil. These investigators did not find Zn deficiency when liming these soils to pH 5.5, but increasing soil pH to 6.5 caused Zn deficiency in soils with less than 1.5 ppm extractable Zn initially. Liming to pH 7.4 gave Zn deficiency symptoms in plants growing on all soils. Schalscha et al. (1968) found 1.6 ppm 0.1N extractable Zn sufficient for plant growth on volcanic ash soils in Chile. Based on the above information, Table 16--Effect of lime and frit on extractable micronutrients in soils from Costa Rica*

Ca as CaCO$_3$	FTE 503 applied, ppm									
	0	30	0	30	0	30	0	30	0	30
	Extractable soil micronutrients+									
	Cu		Zn		Mn		Fe		B	
	ppm									
	San Vito									
0	5.2	5.5	1.6	3.1	168	161	9	15	0.23	0.60
960	4.7	5.1	1.1	1.5	156	138	8	11	--	--
1,920	4.2	4.6	1.0	1.5	86	79	6	7	--	--
2,880	3.1	4.2	1.1	1.5	65	136	5	6	0.17	0.35
	San Isidro									
0	2.2	2.8	1.4	1.6	209	204	8	10	0.21	0.66
760	1.7	2.2	1.1	1.7	117	139	7	7	--	--
1,520	1.3	1.4	1.1	1.9	65	179	4	4	--	--
2,280	1.0	1.0	1.1	1.8	104	155	3	3	0.17	0.39
	Grecia									
0	10.0	10.0	1.9	2.8	75	93	9	11	0.19	0.59
960	9.1	8.7	1.7	2.3	35	62	6	9	--	--
1,920	8.9	8.3	1.8	2.4	28	54	4	5	--	--
2,880	7.5	6.6	1.9	2.1	36	50	2	3	0.26	0.31
	Alajuela									
0	15.4	15.3	2.6	2.9	77	78	11	12	0.47	0.94
890	14.2	13.7	2.5	2.8	25	66	7	8	--	--
1,790	13.1	12.3	2.6	2.7	18	46	5	5	--	--
2,680	7.3	10.1	2.6	2.9	16	50	2	3	0.03	0.64

*Soil samples were taken after 6 weeks' incubation and before initial planting.

+Boron was extracted by hot water and all other micronutrients by 0.1N HCl.

soils from Costa Rica apparently contain adequate Zn for normal plant growth in their natural state.

Concentrations of hot-water soluble B were low in all unlimed soils, except for that from Alajuela (Table 16) Boron values for the other three soils were only slightly above critical concentrations of 0.15 ppm reported by Rogers (1947) for coarse-textured red and yellow Podzolic soils in Alabama. Other investigators have reported higher critical B levels. In Mexico, Flores and Mayagoitia (1959) considered hot-water soluble B concentrations of 0.3 to 3.0 ppm adequate for plant growth.

In general, lime reduced and frit increased concentrations of extractable micronutrients (Table 16). Copper concentrations were reduced by applications of $CaCO_3$ to all soils. In the San Isidro soil, the highest lime rate reduced Cu concentrations to 1.1 ppm whether frit had been applied or not. This value apparently was above the critical soil Cu concentration. All Cu concentrations in the other soils appeared well above critical levels. The effect of lime was less consistent in reducing extractable soil Zn than Cu. Depression of extractable Zn concentrations by liming occurred only in the San Vito soil regardless of frit treatment and in the San Isidro soil without frit (Table 16).

No additional reduction in extractable Zn concentrations was obtained above the first lime increment. In these two soils Zn concentrations were reduced to 1.1 ppm by the first lime increment when frit was not applied. This value is close to the critical 0.1N HCl extractable soil Zn level of 1.0 ppm reported by Wear and Sommer (1948) for corn on Alabama soils, or to 1.3 ppm reported by Viets, Bowan, and Crawford (1954) for various field crops.

Extractable Mn concentrations were high and Fe relatively low in untreated Costa Rican soils. Soil concentrations of extractable Mn and Fe were reduced by lime. No consistent effect of frit on extractable Mn or Fe was obtained. Hot-water extractable B was decreased by lime and increased by frit in all soils (Table 1B). Without added micronutrient frit, soil B was reduced by applications of $CaCO_3$ in three soils to levels just above concentrations considered critical by Wear and Sommer (1948). In limed Alajuela soil without frit, extractable B was only 0.03 ppm which is lower than any reported critical soil B value

Millet growth and chemical composition

Two millet harvests were made at 30-day intervals for the lime x frit experiment. No growth response to either lime or micronutrient frit was obtained for the first harvest from any of the soils from Costa Rica (Table 17). A slight, nonsignificant depression in oven-dry forage yields was obtained for all unlimed soils by applying frit. No effect of either lime or frit on yield was obtained for the second harvest from any of the soils, except for the San Isidro soil (Table 17). Millet yields from the San Isidro soil were increased by the first lime increment and no additional effect was observed from higher $CaCO_3$ rates when frit was not applied. Although there was no significant main effect of frit on forage yields from this soil, there was a lime x frit interaction. With added micronutrients, there were significant increases in oven-dry yields through the highest lime rate. When the first and second harvests of millet grown on San Isidro soil were combined and statistically analyzed, results similar to those for the second harvest were obtained (Table 17, Fig. 6). In the San Isidro soil without frit, there was a significant increase in total herbage with the first lime increment, but the highest $CaCO_3$ rate tended to decrease yields as compared with the first and second increments. A lime x frit interaction was obtained (Fig. 6). With

Table 17--Effect of lime and frit in soils from Costa Rica on yields of millet herbage

Ca as CaCO$_3$	Oven-dry herbage					
	1st harvest		2nd harvest		Total	
	FTE 503		FTE 503		FTE 503	
	-	+	-	+	-	+
ppm	g/pot					
	San Vito					
0	5.5a*	5.3a	3.3a	3.0a	8.8a	8.3a
960	5.3a	5.0a	3.4a	3.2a	8.7a	8.2a
1,920	5.0a	5.1a	3.2a	3.6a	8.2a	8.7a
2,880	4.9a	5.7a	3.1a	3.3a	8.0a	9.0a
	San Isidro					
0	4.0a	3.6a	3.1b	3.1c	7.1b	6.7c
760	4.0a	4.1a	3.7a	3.4bc	7.7a	7.5b
1,520	4.2a	4.2a	3.5a	3.6b	7.7a	7.8ab
2,280	3.9a	4.3a	3.5a	3.9a	7.4ab	8.2a
	Grecia					
0	5.6a	5.4a	4.2a	4.0a	9.8a	9.4a
960	5.8a	5.5a	4.1a	4.3a	9.9a	9.8a
1,920	5.9a	6.0a	4.6a	3.8a	10.5a	9.8a
2,880	6.1a	5.3a	4.2a	4.0a	10.3a	9.3a
	Alajuela					
0	5.6a	5.3a	5.1a	4.8a	10.7a	10.1a
890	5.5a	6.0a	5.3a	4.5a	10.8a	10.5a
1,780	6.0a	5.8a	4.8a	4.9a	10.8a	10.7a
2,680	6.5a	6.1a	5.1a	5.1a	11.6a	11.2a

*Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

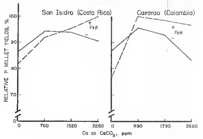


Fig. 6--Effect of lime and frit in San Isidro and Cararao soils on relative herbage yields of millet.

addition of fritted micronutrients, there were positive growth responses to all lime rates.

The effect of lime on average chemical composition of millet grown on soils from Costa Rica, with and without frit, was variable (Table 18). Application of $CaCO_3$ increased forage Ca concentrations from all soils. Magnesium was increased in plants grown on San Vito and San Isidro soils, while there was a decrease in herbage concentrations from Grecia soil and no effect on herbage Mg from the Alajuela soil. Herbage P concentrations from all soils were increased by liming, except for San Isidro soil where no effect was obtained. In general, applications of $CaCO_3$ decreased oven-dry forage K, but the reduction was significant only for the Alajuela soil

The effect of lime on Cu concentrations in millet forage was inconsistent but all are considered above critical Cu concentrations based on the preliminary experiment where 2.7 ppm of Cu in the herbage did not limit growth (Table 13). Forage Zn and Mn concentrations were reduced by lime application to all soils, but there was no effect on Fe (Table 18).

Micronutrient frit had little or no effect on nutrient concentrations in the herbage, except for some micronutrients.

Table 18--Effect of lime in soils from Costa Rica on nutrient concentrations in millet herbage

Ca as CaCO$_3$	Oven-dry herbage* Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	%				ppm			
				San Vito				
0	0.39c+	0.48b	0.26b	2.66a	13.9b	32a	670a	146a
960	0.59b	0.49b	0.29ab	2.45a	13.6b	34a	341b	152a
1920	0.76a	0.56a	0.29ab	2.61a	15.0ab	25b	89c	174a
2880	0.79a	0.51ab	0.32a	2.52a	17.4a	18c	63c	152a
				San Isidro				
0	0.64c	0.86b	0.35a	2.80a	13.9a	43a	750a	155a
760	0.96b	1.03a	0.36a	2.40a	13.5a	39a	354b	159a
1520	1.20a	1.05a	0.36a	2.47a	15.0a	38a	190c	136a
2280	1.24a	1.00a	0.38a	2.38a	14.3a	27b	114d	130a
				Grecia				
0	0.29d	0.87a	0.27b	2.57a	11.9a	37a	341a	90a
960	0.52c	0.77b	0.31ab	2.52a	9.7b	35a	231b	86a
1920	0.71b	0.79ab	0.33a	2.39a	9.9b	31ab	147c	89a
2880	0.82a	0.71b	0.31ab	2.34a	10.5ab	27b	87d	91a
				Alajuela				
0	0.34c	0.58ab	0.20b	4.44a	10.0a	34a	307a	87a
890	0.53b	0.60a	0.25a	4.10ab	9.4a	32ab	191b	95a
1780	0.60a	0.58ab	0.24a	3.96ab	9.2a	31b	92c	90a
2680	0.63a	0.55b	0.25a	3.66b	8.9a	28c	57d	76a

*Nutrient concentrations are for the second harvest.

+Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

Therefore, nutrient concentrations in the forage are presented as averages of treatments with and without frit in tables. Where frit caused differences, data are presented in graphs or in the text. Frit did not affect forage nutrient concentrations from the San Vito soil except for a decrease in Mn (Fig. 7). On the San Isidro soil, frit increased herbage Zn (Fig. 8), and decreased Mn from 374 to 330 ppm. Nutrient concentrations were not affected by frit applied to Grecia soil. Concentrations of Mn (Fig. 7) and Zn (Fig. 8) were increased by frit applications to Alajuela soil.

The positive growth response of millet to lime applied to the San Isidro soil may have been related to a decrease in Mn concentrations to nontoxic levels.

Pangola growth and chemical composition

Five harvests of Pangola were obtained from Costa Rican soils for the lime x frit factorial experiment (Table 19). Forage yields were not significantly affected by application of lime to San Vito or Alajuela soils. However, there was a tendency for yield to increase with the first lime increment to the Alajuela soil. A similar trend was observed for San Isidro. For the first harvest

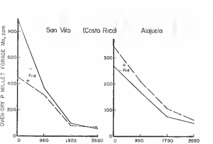


Fig. 7--Effect of lime and frit in San Vito and Alajuela soils on manganese concentrations in the forage of millet.

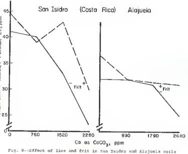


Fig. 8--Effect of lime and frit in San Isidro and Alajuela soils on zinc concentrations in the forage of millet.

Table 19--Effect of lime in soils from Costa Rica on yields of Pangola herbage

Ca as CaCO$_3$	Harvests 1	2	3	4	5	Total
	Oven-dry herbage					
ppm	g/pot					
			San Vito			
0	5.5a*	4.2a	3.4a	6.8a	8.8a	28.1a
960	4.7a	3.3a	3.5a	6.8a	9.3a	27.7a
1,920	4.6a	3.1a	3.0a	6.8a	9.3a	26.7a
2,880	5.0a	3.5a	3.6a	6.7a	8.9a	27.7a
			San Isidro			
0	4.0a	2.3a	2.4a	1.5a	4.1c	14.4a
760	3.9a	2.3a	3.0a	1.9a	4.4bc	15.4a
1,520	3.2a	2.6a	2.9a	1.9a	5.1ab	15.7a
2,280	3.7a	2.4a	2.6a	1.7a	5.3a	15.8a
			Grecia			
0	4.2a	3.4a	3.9a	3.5a	4.4a	19.3a
960	4.6a	3.8a	3.8a	2.4a	5.3a	19.7a
1,920	3.6ab	4.1a	3.8a	3.0a	5.0a	19.6a
2,880	3.0b	4.1a	4.5a	3.3a	5.0a	19.7a
			Alajuela			
0	4.6a	2.0a	3.2a	1.9a	4.3a	15.7a
870	6.2a	2.9a	3.4a	1.8a	5.1a	19.3a
1,890	4.8a	2.6a	3.5a	1.8a	4.3a	16.9a
2,680	5.7a	2.8a	3.1a	1.8a	4.6a	18.5a

*Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

from this soil, herbage yields were significantly increased by the two highest rates of $CaCO_3$. For the first harvest, Pangola growth on Grecia soil was reduced by the two largest lime increments. However, no effect was obtained for other harvests or when total yields were statistically analyzed. Frit application to soils from Costa Rica did not affect Pangola growth. However, the extra P, added to two replications of each soil after the first Pangola harvest increased yields for the fifth harvest from San Vito and San Isidro soils from 8.5 to 9.7 g/pot and 4.2 to 5.3 g/pot, respectively. Phosphorus addition to Grecia soil increased herbage yields for the third, fourth, and fifth harvests, and for the third and fourth harvests from Alajuela soil. Additional P increased total yields of Pangola herbage only on San Vito and Grecia soils. Total yields on these soils increased from 14.1 to 16.6 g/pot and from 17.1 to 22.1 g/pot, respectively. After the third harvest, Pangola plants growing on unlimed Grecia soil, which received frit but no additional P, showed bluish-purple lower leaves. The symptoms were similar to those commonly described as being caused by P deficiency.

The effect of lime application to soils from Costa Rica on nutrient concentrations in Pangola herbage from the third harvest is shown in Table 20. Application of $CaCO_3$ to all soils increased forage Ca. Frit applied to Alajuela soil increased average Ca concentrations in Pangola from 0.49 to 0.54% but had no effect on herbage Ca concentrations from the other soils. Additional P did not affect forage Ca from any of the soils. Inconsistent effects of lime application on forage Mg concentrations were obtained (Table 20). Forage Mg concentrations were increased from San Vito, decreased from Grecia, and unaffected from the other soils by applications of $CaCO_3$. Addition of fritted micronutrients to Alajuela soil decreased herbage Mg from 0.36 to 0.30% but had no effect on forage Mg concentrations when added to the other soils. Extra P added to the Grecia soil decreased overall forage Mg concentrations from 0.31 to 0.20%, but had no effect on herbage Mg from the other soils. Phosphorus concentrations in Pangola forage were not affected by applications of lime or frit. However, extra P increased P concentration in the forage from all soils. The increase in forage P ranged from 0.11 to 0.13% for the Grecia soil to 0.12 to 0.21% for San Vito and San Isidro soils. Forage K concentrations were reduced by liming the Alajuela soil, but this treatment did not affect K in herbage from the other

Table 20--Effect of lime in soils from Costa Rica on nutrient concentrations in Pangola herbage

Ca as CaCO₃	Oven-dry herbage*								
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	S
ppm	%				ppm				
					San Vito				
0	0.39c[+]	0.27b	0.16a	1.86a	6.3a	23a	1,358a	71a	4.4a
960	0.50b	0.29b	0.16a	1.84a	6.4a	18b	607b	66a	--
1,920	0.72a	0.37a	0.17a	2.04a	6.9a	20b	270c	66a	--
2,880	0.76a	0.31b	0.18a	1.97a	6.4a	18b	200c	69a	3.8a
					San Isidro				
0	0.36d	0.25a	0.16a	3.11a	7.2a	27a	1,013a	178a	6.7a
760	0.53c	0.27a	0.14a	3.03a	7.0a	23b	775b	93c	--
1,520	0.63b	0.25a	0.15a	2.79a	6.1a	21b	358c	119b	--
2,280	0.72a	0.26a	0.16a	3.17a	6.9a	16c	187d	112c	5.5b
					Grecia				
0	0.30c	0.31a	0.12a	1.92a	6.1a	19a	638a	68a	6.7a
960	0.47b	0.26b	0.13a	1.81a	6.4a	20a	463b	72a	--
1,920	0.55b	0.24b	0.13a	1.87a	6.6a	21a	317c	66a	--
2,880	0.65a	0.22b	0.13a	1.78a	6.4a	15a	228c	68a	5.5b
					Alajuela				
0	0.35d	0.32a	0.13a	2.68a	8.3a	26a	649a	98a	8.7a
890	0.48c	0.35a	0.11a	2.21b	7.7a	28a	380b	77b	--
1,790	0.56b	0.35a	0.12a	2.43ab	7.8a	23ab	241c	85b	--
2,680	0.66a	0.31a	0.14a	2.09b	8.1a	19b	121d	81b	8.3a

*Nutrient concentrations are for the third harvest, except for S which are for the fifth harvest.

[+] Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

soils. Frit application to soils from Costa Rica did not effect forage K concentrations. Addition of extra P to Grecia soil decreased pangola forage K from 2.1 to 1.6%, but had no effect on forage K from the other soils.

Copper concentrations in pangola forage from the third harvest were not affected by applications of $CaCO_3$ or frit to soils from Costa Rica (Table 20). Phosphorus addition to San Isidro soil decreased herbage Cu concentrations from 7.2 to 6.4 ppm, but had no effect on herbage Cu from the other soils. All pangola herbage Cu concentrations are considered above critical levels for this plant species. Application of $CaCO_3$ to soils from Costa Rica reduced forage Zn concentrations, but the reduction was not significant for Grecia soil (Table 20). Frit applications to soils from Costa Rica did not affect herbage Zn concentrations. On the other hand, extra P applied to all soils decreased forage Zn. The reduction in Zn concentrations by extra applied P were from 23 to 17, 25 to 18, 23 to 15, and 29 to 19 ppm for plants grown on San Vito, San Isidro, Grecia, and Alajuela soils, respectively. Lime applied to all soils decreased forage Mn. Plants grown on unlimed soils contained high Mn concentrations (Table 20). Manganese in forage from unlimed San

Vito soil was above 1300 ppm (Fig. 9), but no growth response to lime was obtained, indicating that Pangola may tolerate high Mn concentrations. Frit application to Alajuela soil increased forage Mn concentrations (Fig. 9) but did not effect Mn concentrations when applied to the other soils. Addition of extra P to Alajuela soil decreased Pangola forage Mn concentrations from 373 to 328 ppm, it had no effect on herbage Mn from other soils. Lime applications to soils from Costa Rica tended to reduce forage Fe (Table 20) but the effect was significant only for San Isidro and Alajuela soils. Frit applications did not affect concentrations of Fe in the herbage from any of these soils. Application of extra P to the San Isidro soil reduced forage Fe concentrations from 138 to 113 ppm, but increased concentrations from the Grecia soil from 60 to 77 ppm.

Boron concentrations in Pangola herbage from the fifth harvest were reduced by liming (Table 20). However, the effect was significant only for San Isidro and Grecia soils. Application of frit to San Isidro and Alajuela soils increased herbage B concentrations from 5.3 to 6.8 ppm and from 7.2 to 9.8 ppm, respectively, but the effect was not significant for the other soils. There was no apparent effect of extra applied P on forage B concentrations.

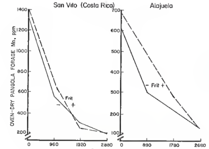


Fig. 9--Effect of lime and frit in San Vito and Alajuela soils on manganese concentrations in forage of Pangola.

The differential effect of lime on Pangola yields is not readily explainable.

For all soils, the highest rate of CaCO$_3$ reduced Zn concentrations in forage (Table 20) to levels close to those reported as critical for several plant species. However, there was no growth response to frit. Bluish-purple lower leaves were observed only on plants from unlimed Gracia soil to which frit had been added. Pangola herbage contained very low P concentrations and it is possible that one or more micronutrients had an antagonistic effect on P metabolism in plants from unlimed soil. Additional soluble Ca in limed soil may have exerted its regulatory role in nutrient absorption.

Lime x Frit Experiment with Soils from Colombia

Chemical properties of the soils

Soil pH values measured in water were increased by the highest rate of CaCO$_3$ application to 6.5, 6.6, 6.0, and 6.2 for Agronomy Area, Cararao, Drainageway, and East Carimagua soils, respectively (Table 21). In 1N KCl, pH values for the same soils were increased to 5.7, 5.8, 5.2, and 5.5 respectively, by the highest levels of lime applied.

Table 21--Effect of lime on some chemical properties of soils from Colombia*

Ca as CaCO$_3$	pH		Exch.	NH$_4$OAc (pH 4.8) extractable			
	H$_2$O	KCl	Al	Ca	Mg	P	K
ppm			ppm				
Agronomy Area							
0	5.3	3.9	192	30	5	0.45	35
690	5.6	4.3	23	430	10	0.45	36
1,390	5.8	5.1	0	1,115	10	0.45	43
2,080	6.5	5.7	0	1,520	10	0.45	38
Cararao							
0	5.0	3.7	270	45	48	1.10	78
890	5.4	4.2	28	585	48	0.65	76
1,790	6.0	5.1	0	1,350	48	0.65	76
2,680	6.6	5.8	0	2,000	30	0.65	73
Drainageway							
0	5.0	4.1	232	15	5	0.45	62
1,150	5.2	4.5	55	360	5	0.45	70
2,290	5.4	4.8	3	1,020	14	0.45	78
3,440	6.0	5.2	0	1,920	10	0.45	92
East Carimagua							
0	5.5	4.1	75	30	10	0.45	22
160	5.6	4.4	20	155	10	0.45	25
320	5.9	5.0	5	250	10	0.45	25
480	6.2	5.5	5	395	5	0.45	18

*Soil samples were taken after 6 weeks' incubation and before initial planting.

Exchangeable Al was reduced by liming. Two-thirds of the theoretical lime required (SMP) to increase soil pH to 6.4 was required to reduce exchangeable Al to 5 ppm or less (Table 21). However, the first lime increment (1/3 of the theoretical lime requirement) was adequate to increase soil pH to 5.2 to 5.6, values now considered adequate for plant growth in soils of the humid tropics. These rates of $CaCO_3$ reduced exchangeable Al to 28 ppm or less, except in the Drainageway soil (Table 21). Exchangeable Al concentration of this magnitude in soils with substantial CEC should be tolerated by many crops from tropical regions if other conditions are adequate. The first lime rate applied increased NH_4OAc (pH 4.8) extractable Ca concentrations to 360 ppm or higher, except in East Carimagua soil. The highest rate of $CaCO_3$ applied increased extractable Ca to 1500 ppm or higher except in the East Carimagua soil (Table 21) where the highest rate of Ca applied was only 480 ppm. The effect of lime applied on extractable soil Mg, P, and K was not consistent (Table 21). Extractable P was reduced by liming Cararao soil but was not affected in the other soils.

The effect of lime and frit on 0.1N HCl extractable soil micronutrients is shown in Table 22. As for most

Table 22--Effect of lime and frit on extractable micronutrients in soils from Colombia*

Ca as	FTE 503 applied, ppm									
	0	30	0	30	0	30	0	30	0	30
	Extractable soil micronutrients+									
CaCO$_3$	Cu		Zn		Mn		Fe		B	
ppm										
Agronomy Area										
0	0.70	1.42	1.42	1.67	2.7	4.8	21	38	0.51	1.12
690	0.51	1.32	2.54	0.94	2.1	4.1	12	22	--	--
1,390	0.51	0.86	3.34	0.96	2.1	3.5	10	13	--	--
2,080	0.31	0.76	3.34	0.94	1.5	2.3	5	10	0.47	0.56
Cararao										
0	0.76	1.17	0.91	2.08	13.0	15.6	85	120	0.48	1.00
890	0.51	0.96	0.54	1.02	9.2	12.7	48	64	--	--
1,790	0.51	0.86	0.46	0.76	8.0	9.3	31	31	--	--
2,680	0.25	0.86	0.39	0.76	5.7	10.0	20	32	0.39	0.66
Drainageway										
0	0.00	0.00	0.47	1.15	1.4	3.9	6	11	0.05	1.15
1,160	0.00	0.14	0.45	0.89	1.6	3.5	5	9	--	--
2,290	0.14	0.14	0.50	0.87	1.4	3.5	4	5	--	--
3,440	0.14	0.00	0.42	0.73	1.4	3.2	3	4	0.25	0.50
East Carimagua										
0	0.31	1.06	0.63	1.14	0.6	1.8	19	21	0.65	0.80
160	0.13	0.96	0.33	1.04	0.6	1.7	16	16	--	--
320	0.13	0.85	0.35	0.83	0.5	1.6	13	14	--	--
480	0.00	0.96	0.28	0.85	0.5	1.5	12	12	0.46	0.70

*Soil samples were taken after 6 weeks' incubation and before initial planting.

+Boron was extracted by hot water and all other micronutrients by 0.1N HCl.

nutrients, concentrations of extractable micronutrients, except Fe, were lower in soils from Colombia than in soils from Costa Rica. Copper concentrations were low in all soils without applied frit. Extractable Cu levels of 0.70 and 0.76 ppm for Agronomy Area and Cararao soils, respectively, may be close to critical soil concentrations. No Cu was extracted from unlimed Drainageway soil, with or without added frit, and only 0.31 ppm were extracted from unlimed East Carimagua soil. On unlimed soil, added frit increased Cu concentrations above 1 ppm in all soils, except for the Drainageway soil (Table 22). Zinc concentrations were higher in Agronomy Area and Cararao soils than in Drainageway and East Carimagua soils. Lime reduced and frit increased Zn concentrations in all soils (Table 22). Extractable Mn was low in East Carimagua and Drainageway soils without added frit. Lime decreased extractable Mn concentrations in all soils, except for the Drainageway when no frit was applied. Extractable Mn was increased in all soils by frit application. Lime reduced and frit increased extractable Fe concentrations in all soils. Similar results were obtained for B, except for Drainageway soil where lime increased B concentrations. Hot-water extractable B was only 0.05 ppm in this soil when unlimed and increased to

0.25 ppm at the highest rate of $CaCO_3$ (Table 22). Lime application may have increased the rate of organic matter decomposition with subsequent release of B and solubilized B-organic matter complexes by increasing microbial activity.

Generally, concentrations of 0.1N HCl extractable Cu and Zn were low in soils from Colombia that did not receive frit. Manganese concentrations were low in all soils from Colombia compared with Costa Rican soils.

Millet growth and
chemical composition

Pearl millet forage yields were increased by liming all soils from Colombia (Table 23). For the first harvest from the Agronomy Area soil without applied frit, there was a positive growth response to the first lime increment but no additional increase from higher rates. When fritted micronutrients were added to this soil, there was a growth response through the second $CaCO_3$ increment. However, yields were very similar with and without frit applied. For the second harvest of millet, oven-dry forage yields from the Agronomy Area soil were increased only by the first lime increment, whether frit was applied or not (Table 23). When the first and second harvests were combined and

Table 23--Effect of lime and frit in soils from Colombia on yields of millet herbage

Ca as	Oven dry herbage					
	1st harvest		2nd harvest		Total	
	FTE 503		FTE 503		FTE 503	
$CaCO_3$	-	+	-	+	-	+
ppm	g/pot					
			Agronomy Area			
0	3.2c*	3.5c	2.2c	2.0b	5.4b	5.5c
690	3.9a	3.8b	2.8a	2.7a	6.7a	6.6ab
1,390	4.0a	4.1a	2.6ab	2.7a	6.6a	6.8a
2,080	3.5b	3.6c	2.3bc	2.5ab	5.8b	6.1b
			Cararao			
0	4.3ab	4.1b	2.7a	2.1b	7.0bc	6.2b
890	4.7a	4.9a	3.0a	3.1a	7.7a	8.0a
1,790	4.5a	5.0a	2.9a	2.9a	7.4a	7.9a
2,680	3.9b	4.7a	2.8a	3.1a	6.7c	7.8a
			Drainageway			
0	1.0b	0.7b	1.4b	0.9b	2.4b	1.6b
1,150	5.7a	5.7a	4.5a	4.5a	10.2a	10.2a
2,290	6.1a	5.8a	4.4a	4.8a	10.5a	10.6a
3,440	5.7a	5.5a	4.4a	4.5a	10.1a	10.0a
			East Carimagua			
0	3.0b	3.1b	0.8b	1.0b	3.8b	4.1b
160	3.9a	4.1a	1.8a	1.9a	5.7a	6.0a
320	4.2a	4.0a	1.7a	1.9a	5.9a	5.9a
480	4.2a	4.2a	1.5a	1.7a	5.7a	5.9a

*Values within columns within subtables followed by different letters are significantly different at 0.05 probability level.

statistically analyzed, maximum growth response on this soil was obtained to the first lime increment when frit was omitted. With addition of frit, maximum yields were obtained with the second lime increment indicating that one or more micronutrients may have limited growth at higher lime rates. On the Cararao soil, forage yields of millet for the first and second harvests was increased by the first lime increment only. Applied frit increased forage yields for the first harvest at the two highest lime rates (Table 23). When the first and second harvests from the Cararao soil were combined, oven-dry forage yields were increased by the first lime increment only. There was a lime x frit interaction (Fig. 6). The highest rate of $CaCO_3$ reduced total yields on Cararao without added frit, but had no effect when frit was added. Although total herbage yields of millet from Cararao soil at the two highest lime rates appeared to be increased by frit, the effect was not significant. In general, the highest lime rates tended to decrease yields from the Agronomy Area and Cararao soils. Oven-dry forage yields of millet from Drainageway and East Carimagua soils were increased by the first lime increment; no effect of additional $CaCO_3$ or frit was obtained. Limited millet growth was obtained from the unlimed Drainageway soil (Table 23). Plants on this soil were deformed, leaves were rolled, and the growth points were necrotic. These symptoms were similar to those observed in Pangola and millet from the preliminary experiment and which have been described by Long and Foy (1970) as "Al-induced Ca deficiency" in barley. Millet plants grown on unlimed East Carimagua soil were chlorotic but did not show rolled leaves or necrotic growth points. None of these symptoms described previously were observed for plants growing on soils which received $CaCO_3$. Growth response of millet to lime on soils from Colombia may have been related to decrease in exchangeable and soluble Al and/or increase in available Ca. Generally, no more than 1/3 the theoretical lime requirement to increase soil pH to 6.4 was required to supply Ca and reduce exchangeable Al to levels satisfactory for optimum plant growth.

Effects of both lime (Table 24) and frit in soils from Colombia on chemical composition of pearl millet were inconsistent. Forage Ca concentrations were increased by liming. Application of $CaCO_3$ increased forage Mg from the Cararao soil, had no effect on forage Mg from the Agronomy Area soil, and decreased it from the other soils (Table 24). However, the decrease in forage Mg concentrations from the Drainageway soil was caused by dilution, since higher

Table 24--Effect of lime in soils from Colombia on nutrient concentrations in millet herbage

Ca as	Oven-dry herbage[*]							
CaCO$_3$	Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	%				ppm			
				Agronomy Area				
0	0.15d[+]	0.44a	0.25c	4.01a	9.9a	46a	131a	121a
690	0.69c	0.48a	0.29c	2.75c	6.9b	35b	120b	109a
1380	0.86b	0.45a	0.33a	2.85bc	6.4b	29c	80c	132a
2080	1.01a	0.46a	0.34a	3.26b	7.4b	20d	53d	137a
				Cararao				
0	0.21d	0.52b	0.29c	3.40a	8.8a	49a	281a	120b
890	0.68c	0.57ab	0.39b	2.70b	5.8c	39b	259a	103b
1780	0.86b	0.57ab	0.44ab	2.71b	5.3c	28c	170b	110b
2680	1.03a	0.62a	0.46a	2.72b	6.7b	19d	115c	224a
				Drainageway				
0	0.08c	0.49a	0.46a	6.01a	5.3a	40a	89a	145a
1150	0.73b	0.32b	0.33c	1.99b	3.2c	21b	57b	91c
2290	0.80ab	0.34b	0.37bc	1.94b	3.9bc	20bc	53b	118c
3440	0.85a	0.37b	0.42ab	2.04b	4.4b	15c	58b	131ab
				East Carimagua				
0	0.21d	0.43a	0.27b	6.76a	7.7a	67a	132a	157a
160	0.66c	0.33c	0.29b	4.57b	8.5a	49b	95b	123b
320	0.80b	0.36b	0.34a	4.37b	8.0a	37c	67c	127ab
480	0.91a	0.37bc	0.37a	5.01b	8.1a	32c	62c	128ab

[*] Nutrient concentrations are for the second harvest.

[+] Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

herbage yields were obtained from limed soil. Phosphorus concentrations in the forage were increased by liming all soils, except the Drainageway. However, as in the case of Mg, higher P concentrations in forage from unlimed Drainageway soil were the result of limited growth. Potassium concentrations in pearl millet herbage were decreased by lime. Copper concentrations in the forage were reduced by liming all soils from Colombia, except East Carimagua, and were increased by application of frit to all soils, except Drainageway (Table 24). Concentrations of Cu in pearl millet grown on Agronomy Area and Cararao soils are shown in Fig. 10. Lime decreased and frit increased Zn and Mn in forage from all soils. The effects of lime and frit on millet herbage Zn from Agronomy Area and Cararao soils are shown in Fig. 11, while the effects of lime and frit on oven-dry forage Mn from Agronomy Area and Cararao soils are shown in Fig. 12. Iron concentrations in pearl millet forage were not affected by liming Agronomy Area soil, but were increased by the highest lime rate on Cararao soil, and tended to decrease by liming the other two soils. With the possible exception of Cu concentrations in millet herbage from the unlimed Drainageway soil without added frit, nutrient concentrations in millet forage were above reported critical levels.

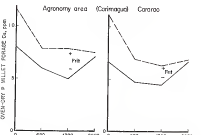


Fig. 10--Effect of lime and frit in Agronomy Area and Cararao soils on copper concentrations in forage of Pangola.

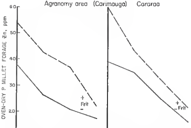


Fig. 11--Effect of lime and frit in Agronomy Area and Cararao soils on zinc concentrations in forage of millet.

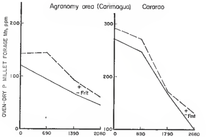


Fig. 12--Effect of lime and frit in Agronomy Area and Cararao soils on manganese concentrations in forage of millet.

Pangola growth and chemical composition

Eight harvests of Pangola were obtained from the lime x frit experiment. The two highest rates of lime applied to the Agronomy Area soil reduced herbage yields. However, Pangola growth from the eighth harvest was increased by liming (Table 25), but application of $CaCO_3$ to this soil did not effect yields for the other harvests or total forage produced. Frit applied to the Agronomy Area soil did not significantly effect individual yields but total yields were increased from 26.9 to 28.1 g/pot. The effect of frit applied to Agronomy Area soil on Pangola growth was significant only at the highest lime rate. Application of extra P to Agronomy Area soil increased overall total herbage yields from 26.1 to 28.9 g/pot. Addition of $CaCO_3$ to Catarso soil did not affect individual oven-dry forage yields of Pangola but increased total yields (Table 25). Frit applied to this soil did not affect herbage yields, but extra applied P increased total forage produced from 27.9 to 30.2 g/pot. Application of $CaCO_3$ to Drainageway soil did not affect herbage yields for the first four Pangola harvests. However, yields for the other harvests and total forage produced were increased by lime. Addition of

Table 25--Effect of lime in soils from Colombia on yields of Pangola herbage

Ca as $CaCO_3$	Harvests								
	1	2	3	4	5	6	7	8	Total
	Oven-dry herbage								
	g/pot								
Agronomy Area									
0	3.4a*	1.9a	1.8a	2.1a	4.3a	3.1a	4.4a	4.7b	26.5a
690	3.2a	2.4a	2.9a	1.4a	3.7a	3.0a	4.7a	5.9a	27.3a
1,390	2.5b	2.9a	3.0a	1.9a	4.4a	3.4a	5.0a	6.4a	28.5a
2,080	2.5b	2.1a	2.9a	1.5a	4.4a	3.0a	4.8a	6.4a	27.5a
Cararão									
0	3.1a	1.9a	2.3d	1.3a	3.8a	3.0a	4.7a	6.1a	26.3c
850	3.0a	2.3a	2.4c	2.1a	4.5a	3.1a	5.4a	7.2a	30.0ab
1,790	3.0a	2.1a	2.7b	1.9a	3.4a	3.2a	5.2a	7.3a	28.9b
2,680	3.2a	2.4a	3.2a	1.8a	4.1a	3.4a	5.5a	7.7a	31.2a
Drainageway									
0	5.2a	2.3a	1.6a	0.6a	1.6b	3.4b	3.3b	4.0b	21.8b
1,150	5.0a	2.2a	1.8a	0.4a	2.4b	3.5b	7.7a	9.8a	32.9b
2,290	4.2a	2.2a	2.2a	0.9a	3.7a	5.7a	7.8a	9.5a	36.3a
3,440	4.5a	2.4a	2.2a	1.2a	3.8a	5.7a	7.3a	9.7a	36.8a
East Carimagua									
0	4.4a	1.6b	2.4a	1.2a	1.5a	1.7a	1.2a	4.0b	17.9b
160	3.9a	1.4b	1.7a	0.7a	1.5a	2.2a	2.9a	5.7a	19.9ab
320	3.1a	2.2a	2.4a	0.9a	1.3a	2.2a	3.4a	5.3ab	20.7a
480	3.6a	2.4a	2.2a	0.7a	1.2a	2.5a	3.2a	6.2a	22.0a

*Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

micronutrient frit to Drainageway soil increased oven-dry forage yields at all lime rates (Fig. 13). Yields from seven harvests were used to calculate relative yields shown in Fig. 13. Extra P increased yields from the fifth harvest from Drainageway soil, but it did not affect yields from other harvests nor total forage produced. Addition of $CaCO_3$ to East Carimagua soil increased forage yields for the second and eighth harvests, and total herbage produced, but did not significantly affect forage yields for the other harvests (Table 25). Fritted micronutrients did not affect Pangola growth on East Carimagua soil, but extra P increased total yields from 16.3 to 24.0 g/pot.

Oven-dry Pangola herbage Ca concentrations for the third harvest were increased by lime (Table 26). Plants grown on unlimed Drainageway soil had low Ca concentrations but the first lime increment increased Ca in forage to concentrations thought adequate for normal Pangola growth. Frit applied to Cararao soil increased herbage Ca concentrations from 0.43 to 0.48%. Extra P applied to Agronomy Area and Cararao soils decreased forage Ca from 0.45 to 0.45% and from 0.49 to 0.43%, respectively. Low forage Mg concentrations were obtained from all treatments (Table 26). Application of $CaCO_3$ reduced Mg in forage, except for the

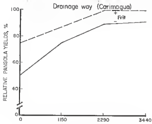


Fig. 13--Effect of lime and frit in Drainageway soil on relative yields of Pangola forage.

Table 26--Effect of lime in soils from Colombia on nutrient concentrations in Pangola herbage

Ca as	Oven-dry herbage*							
CaCO$_3$	Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	%				ppm			
				Agronomy Area				
0	0.15c[+]	0.12a	0.18a	3.01a	5.0a	37a	218a	84a
690	0.46b	0.09b	0.17a	2.92a	4.4ab	27b	107b	82a
1,390	0.61a	0.10b	0.17a	3.19a	4.4ab	22c	76c	76a
2,080	0.65a	0.11ab	0.19a	3.02a	3.6b	14d	59c	82a
				Cararao				
0	0.16c	0.14a	0.16a	2.49a	5.0a	32a	332a	90a
890	0.38b	0.14a	0.16a	2.28a	3.6b	29b	345a	68c
1,780	0.64a	0.16a	0.17a	2.64a	3.5b	23c	217b	77b
2,680	0.65a	0.16a	0.19a	2.38a	2.7b	14d	117c	70c
				Drainageway				
0	0.09d	0.12a	0.13b	2.85a	2.0a	19a	119a	73a
1,150	0.47c	0.05c	0.19a	2.87a	1.8a	19a	45b	79a
2,290	0.58b	0.07bc	0.20a	2.50b	1.9a	17a	40b	73a
3,440	0.69a	0.08b	0.16ab	2.33b	1.7a	13b	42b	73a
				East Carimagua				
0	0.17d	0.12a	0.09c	2.54a	4.9a	37b	181a	81a
160	0.30c	0.06b	0.12b	2.65a	5.0a	45a	148b	88a
320	0.44b	0.06b	0.14ab	2.86a	5.7a	38b	91c	88a
480	0.53a	0.06b	0.16a	2.90a	4.4a	32b	83c	93a

*Nutrient concentrations are for the third harvest.

[+] Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

Cararao soil. On the other hand, forage Mg concentrations were reduced from 0.16 to 0.13% by application of frit to Cararao soil, but it did not affect Mg concentrations when applied to the other soils. Extra P added to Agronomy Area and Cararao soils reduced herbage Mg from 0.12 to 0.09% and from 0.16 to 0.13%, respectively. Application of lime to soils from Colombia tended to increase P concentrations in forage, but the effect was significant only on Drainageway and East Carimagua soils (Table 26). Micronutrient frit did not affect herbage P concentrations, but extra P applied to the Agronomy Area, Cararao, Drainageway and East Carimagua soils increased forage P concentrations from 0.13 to 0.23%, 0.14 to 0.21%, 0.12 to 0.22%, and 0.09 to 0.16%, respectively. Application of $CaCO_3$ to Drainageway soil reduced herbage K concentrations. Frit had no affect on K concentrations in forage. Extra P applied to Cararao and East Carimagua soils reduced K in forage from 2.7 to 2.2 and from 2.9 to 2.5%, respectively.

Oven-dry forage micronutrient concentrations from the third Pangola harvest are shown in Table 26. Addition of $CaCO_3$ to Colombian soils tended to reduce herbage Cu but the effect was significant only from Agronomy Area and Cararao soils (Table 26, Fig. 14). Frit increased forage

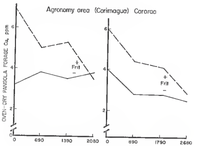


Fig. 14--Effect of lime and frit in Agronomy Area and Cararao soils on copper concentrations in Pangola forage.

Cu from 3.5 to 5.2 ppm, 3.0 to 4.3 ppm, and 3.6 to 6.3 ppm from Agronomy Area, Cararao, and East Carimagua soils, respectively. Extra P decreased Cu in herbage from 4.9 to 3.9 ppm and from 5.8 to 4.2 ppm on Agronomy Area and East Carimagua soils. Copper concentrations in forage from Drainageway soil may have been below critical levels for Pangola. Application of $CaCO_3$ reduced forage Zn concentrations from all Colombian soils. The highest lime rate reduced Zn in herbage from Agronomy Area, Cararao (Fig. 15), and Drainageway soils to concentrations that may have been close to critical levels (Table 26). Similarly, lime decreased forage Mn concentrations. The effect of $CaCO_3$ and frit on forage Mn from Agronomy and Cararao soils is shown in Fig. 16. Frit increased Zn concentrations from 18 to 32 ppm, 20 to 28 ppm, and 23 to 53 ppm in herbage from Agronomy Area, Cararao, and East Carimagua soils, respectively. In these soils, extra applied P decreased Zn in forage from 29 to 21 ppm, 27 to 21 ppm, and 46 to 30 ppm, respectively. Neither micronutrient frit nor extra P affected forage Zn concentrations in Drainageway soil. Iron concentrations in forage were reduced by lime only from the Cararao soil.

The effects of lime applied to all soils from Colombia

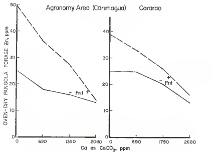


Fig. 15—Effect of lime and frit in Agronomy Area and Cararao soils on zinc concentrations in forage of Pangola.

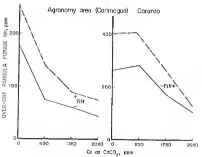


Fig. 16--Effect of lime and frit in Agronomy Area and Cararao soils on manganese concentrations in forage of Pangola.

on nutrient concentrations in herbage from the seventh Pangola harvest, and from herbage from the eighth harvest from East Carimagua soil are shown in Table 27. Forage Ca concentrations from unlimed soils were low, but the first lime increment to Agronomy Area, Cararao and East Carimagua soils increased herbage Ca to levels above those reported as critical for Pangola. Neither frit nor extra P affected Pangola Ca concentrations in forage from the seventh harvest. However, frit applied to the East Carimagua soil decreased Ca in forage from the eighth harvest from 0.20 to 0.17%, but extra P increased herbage Ca from 0.17 to 0.19%. The effect of lime on forage Mg concentrations was inconsistent (Table 27). Addition of frit to Drainageway and East Carimagua soils reduced forage Mg concentrations from 0.23 to 0.21% and from 0.46 to 0.42%, respectively. On the other hand, extra P applied to these soils increased herbage Mg concentrations from 0.20 to 0.24% and from 0.18 to 0.27%, respectively. Lime reduced P concentrations in Pangola herbage from Agronomy Area, Cararao, and Drainageway soils (Table 27). Frit did not affect forage P concentrations, but extra P increased P in herbage from all soils. Phosphorus in oven-dry Pangola from the seventh harvest was lower than the critical concentration of 0.16%

Table 27--Effect of lime in soils from Colombia on nutrient concentrations in Pangola herbage

Ca as CaCO3	Oven-dry herbage*								
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	B
ppm	%				ppm				
	Agronomy Area*								
0	0.11c+	0.27a	0.07b	2.21a	5.1a	28a	70a	61a	7.3
690	0.41b	0.27a	0.09a	1.84bc	4.2a	22a	43b	57a	--
1,390	0.55a	0.29a	0.10a	1.74c	4.4a	25a	41b	62a	--
2,080	0.58a	0.24a	0.11a	1.98b	4.4a	17b	30c	69a	7.1a
	Cararao*								
0	0.14d	0.22a	0.08c	1.93a	4.2a	33a	208a	67a	5.2a
890	0.41c	0.23a	0.10b	1.60b	4.1a	29a	136b	66a	--
1,790	0.57b	0.22a	0.12a	1.73ab	4.1a	21a	81c	64a	--
2,680	0.66a	0.19a	0.11b	1.59b	3.9a	24a	67c	67a	4.6a
	Drainageway*								
0	0.07c	0.21b	0.07a	2.67a	2.0a	18a	51a	45a	6.8a
1,150	0.35b	0.25a	0.08a	1.60b	2.1a	15a	13b	40a	--
2,290	0.48a	0.21b	0.09a	1.42b	1.1a	16a	13b	43a	--
3,440	0.57a	0.22b	0.08a	1.51b	2.3a	12a	15b	48a	6.3a
	East Carimagua*								
0	0.11d	0.18c	0.05a	2.77a	5.7a	40a	99a	99a	9.0a
160	0.15c	0.21bc	0.07a	2.59a	5.4a	29b	79a	79a	--
320	0.20b	0.24ab	0.07a	2.35a	4.4a	27b	76a	65a	--
480	0.26a	0.27a	0.06a	2.46a	5.0a	29b	70a	64a	7.7a

Table 27 (Continued)

Ca as CaCO$_3$	Oven-dry herbage								
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	B
ppm	----------	---------- %	----------	----------	----------	----------	ppm ----------	----------	----------
				East Carlxague‡					
0	0.08d	0.40c	0.15a	3.47a	5.8a	34a	114a	63a	
160	0.14c	0.42bc	0.11a	2.79a	4.1b	22b	86ab	60a	
320	0.23b	0.48a	0.13a	2.74a	4.4b	20b	66bc	61a	
480	0.28a	0.45ab	0.12a	2.73a	3.8b	19b	49c	54a	

*Nutrient concentrations are for the seventh harvest

†Values within columns within subtables followed by different letters are significantly different at the 0.05 probability level.

‡Nutrient concentrations are for the eighth harvest.

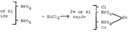
reported by Andrew and Robins (1971). Application of $CaCO_3$ decreased herbage K in herbage from all soils, except East Carimagua. Frit applied to Agronomy Area soil decreased K in herbage from 2.02 to 1.87%. Similarly, extra P added to Agronomy Area, Cararao and East Carimagua soils decreased forage K from the seventh harvest from 2.02 to 1.87%, 1.81 to 1.62% and 2.85 to 2.23%, respectively.

Concentrations of micronutrients in oven-dry Pangola herbage from the seventh harvest are shown in Table 27. Liming these soils did not affect forage Cu concentrations from the seventh harvest, but it decreased Cu in forage from the eighth harvest from East Carimagua soil. Frit increased forage Cu from the seventh harvest from 3.2 to 4.9 ppm and from 1.5 to 2.3 ppm for Cararao and Drainageway, respectively. This treatment increased Cu in forage from the eighth harvest on East Carimagua soil from 3.0 to 6.0 ppm. The main effect of extra P applied to Agronomy Area, Cararao and East Carimagua soils was to decrease herbage Cu concentrations from 5.0 to 4.0 ppm, 4.5 to 3.6 ppm, and 6.5 to 3.6 ppm, respectively. This probably was a result of dilution from increased growth. Like the third Pangola harvest, Cu concentrations in forage from the seventh harvest appeared above critical levels, except from the Drainageway soil. Forage Zn concentrations were decreased by liming (Table 27) and the highest rate of lime applied to Drainageway soil reduced Zn concentrations to values that may have been near the critical level. Addition of frit to Agronomy Area and East Carimagua soils increased herbage Zn concentrations from the seventh Pangola harvest from 18 to 28 ppm and from 24 to 37 ppm, respectively. This treatment increased herbage Zn concentrations from the eighth harvest on East Carimagua soil from 18 to 29 ppm. Application of extra P generally reduced Zn concentrations in forage from all soils. Liming these soils decreased herbage Mn concentrations (Table 27). This effect was very pronounced for the Drainageway soil. Frit applied to Agronomy Area, Drainageway, and East Carimagua soils increased herbage Mn from 37 to 55, 18 to 28, and 64 to 93 ppm, respectively. Conversely, extra P decreased forage Mn from 106 to 57 ppm from East Carimagua soil. Lime and frit applications did not significantly influence herbage Fe concentrations, but extra P applied to East Carimagua soil decreased forage Fe from 97 to 57 ppm. No effect of extra applied P on herbage Fe concentrations from the other soils was obtained. Although liming soils from Colombia tended to decrease Pangola forage B concentrations, the effect was not statistically significant. Application of frit to these soils appeared to increase herbage B concentrations, but this effect was significant only for the Agronomy Area soil where herbage B concentrations increased from 5.6 to 6.5 ppm. No apparent effect of extra applied P on forage B concentrations was observed.

The tendency for decreased yields of Pangola forage from the first harvest (Table 25) following lime addition may have resulted from reduction in herbage Mg concentrations from unfavorable soil Ca/Mg ratios. Tisdale and Nelson (1966) stated that liming acid soils may cause Mg deficiency in plants. Furthermore, Mg deficiencies in plants may occur if the exchangeable Ca/Mg ratio is too high (Mortvedt and Cunningham, 1971) which may have been the case in these soils. The general increase in Pangola yields for the seventh harvest following application of soluble Mg was caused by increased Mg concentrations in plants. Since an additional basal P application was made after the seventh harvest, yields from the eighth harvest may have been further increased by improved P nutrition. The increase in total yields by lime may have been related to decreased soluble and exchangeable Al and/or increased available Ca in these soils.

Addition of P, after the first Pangola harvest, to two replications of Drainageway and East Carimagua soils resulted in chlorotic plants with speckles and streaks along the leaves. The midribs and veins remained darker in color. Analytical data from the third harvest indicated that the symptoms were caused by Mg and/or micronutrient deficiencies (Table 26). After the third Pangola harvest, dark purple leaves were observed on plants from all treatments on Drainageway and East Carimagua soils without additional P. These symptoms were also observed on unlimed Cararao soil. Application of $CaCO_3$ may have improved P nutrition in this soil. Before the fourth harvest was made plants on Drainageway soil with additional P were chlorotic with reddish leaf tips. Similar disorders were observed for plants grown on unlimed East Carimagua soil to which extra P had been added. These symptoms were believed to be P-induced Zn and/or Cu deficiency. The antagonistic effect of P on Zn uptake has been studied extensively (Stanton and Burger, 1967; Boawn and Brown, 1968, Warnock, 1970; Brown, Krantz, and Eddings, 1970; Lindsay, 1972b). Generally Pangola forage Zn and Cu concentrations were low from Drainageway soil, whether or not frit was applied. Low forage Zn concentrations were found at the highest rate of lime in all soils when frit was omitted. In these soils, application of high lime and P rates may induce Zn deficiencies.

Stanton and Burger (1967) believed that various oxides of Fe and Al can fix Zn through polyvalent phosphate ions as follows:



They suggested that Zn bound to hydrated Fe oxide in soils through polyvalent phosphate ions is unavailable to plants. Furthermore, these investigators reported that in the absence of phosphate ions, only the more crystalline hydrated Fe oxides, such as goethite, fix Zn in forms unavailable to plants. On the other hand, Lindsay (1972a) suggested that $Zn_3(PO_4)_2.4H_2O$ would be a good Zn and P fertilizer. Olsen (1972) listed four possible mechanisms for the effect of P on Zn absorption by plants: (1) a P-Zn interaction in the soil, (2) a slower rate of translocation of Zn from plant roots to the tops, (3) a dilution effect on Zn concentrations in the tops caused by a growth response to P, and (4) a metabolic disorder within plant cells related to an imbalance between P and Zn since an excessive concentration of P may interfere with the metabolic functions of Zn at certain sites in the cells

Zinc x Copper Experiment

This experiment was conducted to study the effect of rates of Zn and Cu applied to the soil on growth and chemical composition of Pangola, and on the quantity of micronutrients extracted by 0.1N HCl in Drainageway and East Carimagua soils.

Pangola growth and chemical composition on East Carimagua soil

The effect of individual treatments on oven-dry herbage yields of Pangola are shown in Appendix B, Table 40. Maximum yields of Pangola were obtained with the application of 5.0 ppm each of Zn and Cu. Although applied Zn tended to increase forage yields, the effect was not significant (Table 28). Applied Cu tended to increase herbage yields of Pangola, but they were significantly increased only for the third harvest and for total herbage produced (Table 29). Maximum response of Pangola was obtained with the second Cu increment (5.0 ppm).

Table 28--Effect of zinc in East Carimagua soil on yields and nutrient concentrations in Pangola herbage

Zn applied	Harvests				Oven-dry herbage*							
	1	2	3	Total	Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	g/pot				%				ppm			
0.0	3.7a+	7.1a	3.5a	14.4a	0.24a	0.30a	0.15ab	2.25b	4.8a	29d	47bc	74a
2.5	2.7a	7.7a	3.8a	14.2a	0.25a	0.30a	0.15ab	2.81a	5.1a	42c	57a	73ab
5.0	3.5a	7.7a	3.7a	14.9a	0.23a	0.30a	0.17a	2.45b	5.2a	59b	53ab	67ab
10.0	3.9a	8.0a	3.8a	15.7a	0.23a	0.30a	0.14b	2.22b	4.9a	74a	43c	65b

*Nutrient concentrations are for the first harvest and are averages of all Cu levels.

+Values within a column followed by different letters are significantly different at the 0.05 probability level.

Table 29--Effect of copper in East Carimagua soil on yields and nutrient concentrations in Pangola herbage

Cu Applied	Harvests 1	2	3	Total	Oven-dry herbage* Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	g/pot				%				ppm			
0.0	3.1a+	7.2a	3.3b	13.5b	0.24a	0.31a	0.16a	2.52a	3.54c	53a	54a	77a
2.5	3.5a	7.5a	3.6ab	14.5ab	0.24a	0.30a	0.14a	2.41a	4.86b	51ab	47a	67b
5.0	3.7a	7.9a	4.1a	15.7a	0.24a	0.31a	0.15a	2.28a	5.17b	45b	49a	67b
10.0	3.5a	8.0a	3.9ab	15.4a	0.23a	0.30a	0.15a	2.51a	6.36a	53a	49a	68b

*Nutrient concentrations are for the first harvest and are averages of all Zn levels.

+Values within a column followed by different letters are significantly different at the 0.05 probability level.

The effect of individual treatments in East Carimagua soil on nutrient concentrations in Pangola herbage for the first harvest is shown in Appendix B, Table 41. Application of Zn did not affect herbage concentrations of Ca or Mg, and had little effect on forage P or K concentrations from the first harvest (Table 28). Applied Zn did not influence forage Cu, but it increased herbage Zn, and decreased Fe concentrations. Forage Mn concentrations were enhanced by the first Zn increment and were reduced by the highest rate. Application of Cu to East Carimagua soil did not affect forage concentrations of Ca, Mg, P, K, or Mn from the first Pangola harvest (Table 29). However, applied Cu increased herbage Cu and decreased Fe concentrations. Forage Zn concentrations were decreased through the second increment of applied Cu (Table 29).

Herbage nutrient concentrations from the second harvest for each treatment in East Carimagua soil are shown in Appendix B, Table 42. Applied Zn had no effect on forage Ca, Mg, P, K, or Fe concentrations (Table 30). The first Zn increment increased Cu concentrations, but they were depressed by the highest rate of applied Zn. Applied Zn increased forage Zn concentrations. Similarly, Mn concentrations in Pangola were increased through the second Zn

Table 30--Effect of zinc in East Carimagua soil on nutrient concentrations in Pangola herbage, and 0.1N HCl extractable micronutrients

Zn applied	Oven-dry herbage*								Soil micronutrients			
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
ppm	%							ppm				
0.0	0.31a⁺	0.52	0.12a	1.54a	3.16ab	20d	18bc	68a	4.47a	0.46d	0.30b	20a
2.5	0.32a	0.52	0.12a	1.67a	3.47a	29c	20ab	85a	4.20a	3.00c	0.30b	20a
5.0	0.29a	0.49	0.12a	1.55a	3.23ab	41b	22a	60a	5.14a	5.65b	0.31ab	19a
10.0	0.29a	0.47	0.11a	1.50a	2.75b	52a	16c	69a	4.30a	13.91a	0.38a	20a

*Nutrient concentrations in herbage are for the second harvest and in soil from samples taken following the second harvest, and are averages of all Cu levels.

⁺Values within a column followed by different letters are significantly different at the 0.05 probability level.

increment, but reduced by the highest rate (Table 30).

For the second harvest applied Cu did not influence herbage Ca, Mg, P, K, Mn, or Fe concentrations. However, added Cu increased forage Cu and decreased forage Zn concentrations (Table 31).

Extractable micronutrients in East Carimagua soil

Soil samples for micronutrient determinations were taken after incubation but before planting and after the second Pangola harvest. Micronutrients were extracted by 0.1N HCl solution. Before planting, soil pH values measured in water and KCl, were 5.8 and 4.7, respectively, but after the second harvest the average soil pH values had decreased to 5.5 and 4.6 when measured in water and KCl, respectively. There was no effect of Zn or Cu on soil pH.

Before planting, East Carimagua soil contained 0.25, 0.61, 0.50, and 10.3 ppm of extractable Cu, Zn, Mn, and Fe, respectively. The effects of individual treatments on extractable micronutrients in this soil are shown in Appendix B, Table 40. There was a decrease in extractable Zn and Fe, an increase in Mn, but no effect on extractable Cu concentrations with time. Zinc application did not affect extractable soil Cu or Fe, but increased extractable Zn and

Table 31--Effect of copper on nutrient concentrations in pangola herbage, and 0.1N HCl extractable micronutrients in East Caramagua soil

Cu added	Oven-dry herbage*								Soil micronutrients			
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
ppm	----------	%	----------		----------	----------	----------	---------- ppm	----------	----------	----------	----------
0.0	0.31a⁺	0.51a	0.13	1.66a	2.1c	42a	19a	79a	0.30d	4.27bc	0.33a	20a
2.5	0.30a	0.50a	0.12	1.66a	3.4ab	33b	20a	79a	3.20c	7.00a	0.31a	20a
5.0	0.30a	0.50a	0.11	1.45a	3.2b	32b	19a	67a	5.25b	6.10b	0.30a	19a
10.0	0.29a	0.49a	0.11	1.49a	3.9a	36ab	19a	77a	9.36a	4.65c	0.34a	20a

*Nutrient concentrations in forage are for the second harvest and in soil from samples taken following the second harvest, and are averages of all Zn levels.

⁺Values within a column followed by different letters are significantly different at the 0.05 probability level.

Mn concentrations (Table 30). This soil apparently contained enough Zn for the first two or three Pangola harvests. However, extractable Zn concentrations in untreated soil were lower than the 0.93 ppm considered critical by Viets, Bowan, and Crawford (1954). It is possible that within a short period of time after initiation of cropping, Zn application may be required for maximum plant growth on this soil. The plant species used may also be important in determining critical nutrient levels. The different proportions of colloids may be important in determining nutrient availability.

Application of Cu to East Carimagua soil increased extractable Cu, but did not influence extractable Mn or Fe. The first Cu increment increased the amount of Zn extracted, but the highest rate of application reduced it (Table 31). Since there was a positive response of Pangola to Cu application for the third harvest, it would appear that the critical level of 0.1N HCl extractable Cu in this soil is approximately 0.30 ppm.

Concentrations of Cu in herbage of 2.1 ppm in Pangola were associated with deficient plants, whereas 3 4 ppm indicated adequate Cu in herbage (Table 31). Therefore, it is apparent that the critical Cu concentration for

Pangola is between these two values.

Pangola growth and chemical composition on Drainageway soil

The effects of treatment combinations on growth of Pangola are shown in Appendix B, Table 43. Applied Zn did not affect oven-dry yields of Pangola herbage from the first harvest. However, there was a significant increase in Pangola yields by applied Zn from the second and third harvests, and for total forage produced (Table 32). Oven-dry yields of Pangola herbage were significantly increased by the first Zn increment (5.0 ppm) but no further increase was obtained from additional Zn. Applied Cu increased forage yields of Pangola, but the effect was not significant from the first harvest. Forage yields from the second and third harvests, and total herbage were significantly increased by the first Cu increment (Table 33). Although yields from the third harvest and total herbage were increased by the second and third Cu increments, the effect was not significant. Yields of Pangola forage were not affected by the application of 2 ppm B. In general, maximum oven-dry yields of Pangola forage were obtained with the application of 5 ppm Zn and 60 ppm of Cu.

Table 32--Effect of zinc in Drainageway soil on yields and nutrient concentrations in Pangola herbage

Zn applied	Harvests				Oven-dry herbage*							
	1	2	3	Total	Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	g/pot				%				ppm			
0	4.0a+	4.1b	2.7b	10.8b	0.40a	0.18a	0.25a	2.14b	5.3a	13d	57a	102a
5	4.3a	7.4a	3.9a	15.5a	0.36b	0.13b	0.15b	2.41a	4.8a	26c	49bc	80b
10	3.8a	7.4a	3.9a	15.2a	0.37b	0.13b	0.15b	2.56a	4.9a	38b	55ab	78b
20	4.1a	6.8a	3.0ab	14.1a	0.36b	0.14b	0.14b	2.03b	5.7a	68a	46c	79b

*Nutrient concentrations are for the first harvest and are averages of all Cu levels

+Values within a column followed by different letters are significantly different at the 0.05 probability level.

Table 33--Effect of copper in Drainageway soil on yields and nutrient concentrations in Pangola herbage

Cu applied	Harvests 1	2	3	Total	Oven-dry herbage[a] Ca	Mg	P	K	Cu	Zn	Mn	Fe
ppm	-------- g/pot			--------	------------ %			------------	-------- ppm			--------
0	3.8a[+]	4.5b	2.2b	10.5b	0.38a	0.15ab	0.19a	2.32a	2.1c	45a	52a	94a
15	4.2a	6.6a	3.4a	14.2a	0.37a	0.16a	0.19a	2.35a	5.4b	36b	50a	94a
30	4.2a	7.4a	3.6a	15.2a	0.38a	0.14b	0.16b	2.18a	5.4b	31b	54a	77b
60	4.0a	7.2a	4.3a	15.7a	0.36a	0.14b	0.16b	2.29a	7.7a	34b	51a	74b

[a] Nutrient concentrations are for the first harvest and are averages of all Zn levels.

[+] Values within a column followed by different letters are significantly different at the 0.05 probability level.

The effects of treatments of Drainageway soil on nutrient concentrations in oven-dry Pangola herbage from the first harvest are shown in Appendix E, Table 44. Applied Zn reduced forage Ca, Mg, P, and Cu concentrations. Conversely Zn applications through the second increment increased forage K, but the highest rate applied significantly reduced forage K concentrations as compared with the maximum (Table 32). Oven-dry forage Zn concentrations were increased by addition of Zn, but forage Mn and Fe concentrations were reduced by this treatment. There was no apparent effect of Zn application on forage N concentrations (Appendix E, Table 44) For the first harvest, application of Zn did not affect total uptake of Ca, Cu, Mn, or Fe. However, added Zn reduced uptake of Mg and P. The first Zn increment increased K uptake, but there was no effect from the highest rate of application. All levels of Zn applied significantly increased Zn uptake

Copper applied to Drainageway soil did not influence oven-dry forage Ca, K, or Mn concentrations from the first harvest (Table 33). However, Cu addition decreased forage P, Zn, and Fe and increased Cu concentrations. For P and and Fe, this effect was significant only after the second Cu increment, while Zn was reduced by the first Cu increment and no further reduction in Zn concentration was obtained from additional Cu. Applied Cu apparently decreased herbage N concentrations (Appendix B, Table 44). For the first harvest, applied Cu increased Cu uptake, but this treatment did not affect uptake of other nutrients.

The effects of treatments of Drainageway soil on nutrient concentrations in oven-dry Pangola herbage for the second harvest are shown in Appendix B, Table 45. The first Zn increment reduced forage concentrations of all nutrients, except Zn. Oven-dry Pangola herbage Zn concentrations were increased by all Zn rates (Table 34). Although applied Zn reduced forage nutrient concentrations, this treatment did not significantly affect uptake of Ca, K, or Mn, indicating that the reduction in forage concentrations of these nutrients was caused by dilution because of increased yields by Zn application. Nevertheless, applied Zn decreased Mg, P, and Cu and increased Zn and Fe uptake.

For the second harvest, applied Cu decreased forage nutrient concentrations, except for Cu which was increased (Table 35). Herbage concentrations of K, Zn, and Mn were reduced by the first Cu increment, but no further decrease in concentrations was obtained from additional Cu. Forage

Table 34--Effect of zinc in Drainageway soil on nutrient concentrations in Pangola herbage, and 0.1N HCl extractable micronutrients

Zn applied	Oven-dry herbage*								Soil micronutrients			
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
ppm	%				ppm							
0	0.70a[+]	0.56a	0.48a	2.68a	6.8a	10d	67a	106a	0.56a	0.71d	1.48c	2.31b
5	0.43b	0.20c	0.14b	1.75b	3.1c	17c	40b	70c	0.67a	2.89c	1.69ab	3.41a
10	0.44b	0.19c	0.14b	1.80b	3.7bc	26b	42b	67c	0.59c	4.58b	1.78a	3.29a
20	0.40b	0.29b	0.12b	1.74b	4.3b	50a	40b	90b	0.73a	12.23a	1.61bc	2.49b

*Nutrient concentrations in herbage are for the second harvest and are average of all Cu levels.

[+] Values within a column followed by different letters are significantly different at the 0.05 probability level.

Table 35--Effect of copper in Drainageway soil on nutrient concentrations in Pangola herbage, and 0.1N HCl extractable micronutrients

Cu applied	Oven-dry herbage*								Soil micronutrients			
	Ca	Mg	P	K	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe
ppm	%				ppm							
0	0.59a^{+}	0.36a	0.27a	2.40a	1.83c	34a	53a	90a	0.19c	3.07b	1.59a	2.64b
15	0.51b	0.31b	0.23b	1.88b	5.09b	21c	45b	93a	0.34c	6.02a	1.63a	2.74b
30	0.49bc	0.30bc	0.21b	1.89b	5.24ab	23bc	47ab	76b	0.53b	5.47a	1.63a	3.05a
60	0.45c	0.27c	0.16c	1.80b	5.77a	25b	44b	73b	1.50a	5.84a	1.72a	3.08a

*Nutrient concentrations are for the second harvest and are average of all Zn levels.

+Values within a column followed by different letters are significantly different at the 0.05 probability level.

Ca, Mg, and P concentrations were decreased through the highest rate of Cu applied (Table 35). Herbage Fe concentrations were decreased by the second and third Cu increments only. Although Cu applications reduced concentrations of most nutrients, this treatment increased uptake of Ca, Mg, P, K, Cu, and Fe, indicating that the reductions in concentrations were caused by dilution by increased herbage yields. Zinc uptake was not affected by applied Cu.

Regression analyses of the effects of Zn and Cu on yields from the second and third harvests, total herbage, and herbage P and Mg from the first and second harvests from Drainageway soil showed that the quadratic model fitted the regression equations for all variables better than the linear model (Table 36). Regression coefficients and coefficients of determination for the quadratic model for the above variables are shown in Table 37. Higher coefficients of determination were obtained for P and Mg concentrations for the second harvest. Zinc had more effect on all the dependent variables than Cu.

The marked negative effect of applied Zn on herbage P concentrations and uptake may be the reason for the

Table 36--Coefficients of determination for two regression models for dependent variables on Drainageway soil

Dependent Variables	Model: Linear	Model: Quadratic
	R^2	R^2
Second harvest	0.29**	0.60**
Third harvest	0.15*	0.26**
Total herbage	0.24**	0.46**
Phosphorus[†]	0.47**	0.73**
Phosphorus[‡]	0.50**	0.80**
Magnesium[†]	0.22**	0.64**
Magnesium[‡]	0.25**	0.82**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

[†] Concentrations in herbage from the first harvest.

[‡] Concentrations in herbage from the second harvest.

Table 37.--Regression coefficients for dependent variables on Drainageway soil

Dependent Variables	Source					
	Y Intercept	Zn	Cu	Zn^2	Cu^2	Zn x Cu
	B values					
Second harvest	2.513	0.586	0.147	-0.023	-0.002	0.000
Third harvest	1.778	0.234	0.065	-0.011	-0.001	0.000
Total harbage	8.323	0.785	0.228	-0.034	-0.003	0.002
Phosphorus†	0.279	-0.019	-0.002	0.001	0.000	0.000
Phosphorus‡	0.543	-0.063	-0.004	0.002	0.000	0.000
Magnesium†	0.191	-0.011	-0.000	0.000	-0.000	0.000
Magnesium‡	0.591	-0.003	-0.003	0.003	0.000	0.000

†Concentrations in herbage from the first harvest.

‡Concentrations in herbage from the second harvest.

decreased yields obtained by Burgos[1] when he applied Zn to unfertilized soils from Guatemala.

Data in Appendix B, Table 45 indicate that the critical forage Zn concentration in Pangola lies between 10 and 13 ppm, and Cu between 2.0 to 3.2 ppm.

Extractable micronutrients in Drainageway soil

After incubation but before planting, soil pH values measured in water and KCl were 6.3 and 5.5, respectively. After the second harvest, average pH values had decreased to 5.7 and 5.3 when measured in water and KCl, respectively. After incubation but before planting, Drainageway soil contained 0.59, 0.00, 2.00, and 1.65 ppm of extractable Zn, Cu, Mn, and Fe, respectively. The effect of Zn and Cu combinations on extractable micronutrient concentrations is shown in Appendix B (Table 43). After the second harvest the average concentrations of extractable Zn, Cu, and Fe had increased to 0.71, 0.13, and 2.48 ppm, respectively (Table 34). On the other hand, extractable Mn concentrations had decreased to 1.54 ppm. Applied Zn tended to increase extractable Cu but the effect was not significant. However, Zn application increased extractable Zn concentrations. Extractable Mn concentrations were increased through the second Zn increment. Extractable Fe was increased through the second Zn increment.

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[1] Burgos, see footnote 1, page 51.

Copper applications increased extractable Cu, Zn, and Fe concentrations, but this treatment did not influence extractable Mn concentrations (Table 35). Extractable Zn concentrations were increased by the first Cu increment, but no further increase was obtained from additional Cu. Only the second and third Cu increments significantly increased Fe concentrations. The increase in extractable Zn, Cu, and Fe concentrations with time may have been related to increased soil acidity.

Zinc-P interactions have been studied widely but in most cases the effect on plant growth is P-induced Zn deficiency. However, decrease in P absorption following addition of Zn has also been reported. Brown et al. (1970) reported that P deficiency symptoms were accentuated by Zn application to Yolo fine sandy loam and Grangeville loamy fine sand.

SUMMARY AND CONCLUSIONS

Surface soil samples (0 to 18 cm) and profile samples to a minimum depth of 150 cm were collected in August and September 1972, from four sites in Costa Rica and four sites in the eastern Llanos of Colombia. Soil profiles were described in the field; particle size distribution, pH values, and exchangeable Al were determined in the laboratory. All greenhouse experiments and laboratory analyses were conducted at the University of Florida, Gainesville.

Costa Rican soils, sampling sites 1 through 4, were called San Vito, San Isidro, Gracia, and Alajuela, respectively. Soils from Costa Rica were classified as Ultisols, except the San Isidro soil which was placed in the Oxisol order. According to field estimates, these surface soils had loam textures, except for San Isidro which was clay loam.

Colombian soils, sampling sites 5 through 8, were called Agronomy Area, Cararao, Drainageway, and East Carimagua, respectively. Agronomy Area and Drainageway soils were classified as Oxisols, while Cararao and East Carimagua soils were placed in the Ultisol order. Surface textures of the Agronomy Area, Cararao, Drainageway, and East Carimagua soils were clay loam, clay, loam to clay loam, and sandy loam, respectively.

Except for the Drainageway soil, soils from Colombia were more acid, had lower CEC, contained less organic matter, had lower concentrations of total elements, except Na, and retained less P than Costa Rican soils. Colombian soils also had lower concentrations of NH_4OAc (pH 4.8) extractable Ca and Mg, and extractable micronutrients, except Fe and B. High extractable Mn concentractions were characteristic of the Costa Rican soils. Soils from Colombia, except East Carimagua, contained higher amounts of 1N KCl exchangeable Al than the soils from Costa Rica. Extractable NO_3-N and SO_4-S were relatively low in all soils. pH values in surface soils from Costa Rica measured in water and 1N KCl were 5.2 and 4.4, respectively. Surface soils from Colombia had pH values measured in water and KCl which ranged from 4.6 and 3.8 in Cararao to 5.3 and 4.3 in Drainageway soil, respectively. All soils showed high pH-dependent CEC. At pH 7.0, CEC values were approximately twice as large as those measured at pH 4.8. Organic matter in soils from Costa Rica ranged from 6.3 to 11.3% in San Isidro and Grecia, respectively. Colombian soils had organic matter contents which ranged from 1.7 to 20.8% in East Carimagua and Drainageway soils, respectively.

An incubation trial with lime was conducted to determine the effect of $CaCO_3$ on soil pH and 1N KCl exchangeable Al in all surface soils. Calcium was applied as $CaCO_3$ at 0, 50, 100, 200, 300, 400, 800, 1200, and 1600 ppm. Sufficient water was added to increase soil moisture approximately to field capacity and incubated for 7 weeks. Generally, incubation without lime reduced exchangeable Al and increased soil pH values. Soils from Costa Rica required 800 ppm Ca to reduce exchangeable Al to 10 ppm or less. Agronomy Area soil from Colombia required 800 ppm Ca to reduce exchangeable Al to 10 ppm, while 800 ppm Ca reduced exchangeable Al to 36 and 26 ppm in Cararao and Drainageway soils, respectively. On the other hand, only 200 ppm of Ca were required to reduce exchangeable Al to 5 ppm in East Carimagua soil.

Lime x frit greenhouse experiments were conducted to determine the effect of applied $CaCO_3$ and frit on growth and composition of warm-season grasses, and on some chemical properties of the soils.

A preliminary experiment to study effects of lime and frit in Leon fine sand (Aeric Haplaquod) from Florida on three warm-season grasses was established. The initial data indicated the possibility of Cu deficiency. For this reason, Cu treatments were superimposed on soil without frit at 0, 0.5, 1.0, and 2 ppm Cu as $CuSO_4 \cdot 5H_2O$ after the first bahia harvest. Forage yields of Pangola and millet were increased by lime application. Bahia yields were increased by liming only when frit was omitted; when frit was applied, yields were high at all lime levels. Millet yields were increased through the highest lime rate, but maximum Pangola growth was obtained with the first lime increment. Added frit increased forage yields of Pangola and bahia at all lime rates but had no effect on millet growth. Forage yields of bahia were increased by the first Cu increment but no further increase in yields was obtained from additional Cu. Copper in forage of bahia increased from 1.4 ppm without applied Cu to 3.4 ppm at the highest rate. Yields of millet forage were not affected by applied Cu. However, Cu in forage increased from 2.7 to 7.5 ppm as added Cu was increased from 0 to 2 ppm. The critical Cu concentration in bahia forage was 2.5 ppm, while for millet it was 2.7 ppm or less.

Four soils from Costa Rica and four from Colombia were used in the primary lime x frit greenhouse experiment. The

SMP buffer method was the criterion used to select lime rates. Calcium as $CaCO_3$ was applied at 0, 1/3, 2/3, and 3/3 the theoretical amounts required to increase soil pH to 6.4. Frit was applied at 0 and 30 ppm. To determine whether low soil P was limiting growth, P equal to the initial quantities was applied to two replications of all soils after the second Pangola harvest. Pangola forage analyses from the third harvest indicated extremely low Mg concentrations, so a uniform application of 50 ppm Mg as $MgSO_4$ was applied to all soils from Colombia following the fifth and sixth harvests, and as $Mg(NO_3)$ following the seventh harvest.

Generally, pH and NH_4OAc (pH 4.8) extractable Ca increased, and extractable Mg and exchangeable Al decreased in unlimed soils with incubation. Applied $CaCO_3$ increased soil pH and extractable Ca, and decreased exchangeable Al. Added lime had little or no effect on extractable P and K. In general, lime decreased and frit increased concentrations of extractable soil micronutrients.

Application of lime increased millet forage yields from San Vito and from all Colombian soils. Maximum response was generally obtained with the first lime increment. No response by millet to frit application was obtained.

Applied $CaCO_3$ increased forage Ca and P in millet, but had varied effect on K and Mg in the forage. Added frit tended to decrease Mg and P in forage. In general, applied $CaCO_3$ reduced and frit increased forage micronutrient concentrations, except Fe. The growth response by millet on San Isidro soil from Costa Rica may have been related to high Mn concentrations, while in Colombian soils the high exchangeable and soluble Al and/or low available Ca may have been the main growth limiting factors.

In general, Pangola growth was not affected by applications of lime or frit to Costa Rican soils. Additional P increased total Pangola herbage only from San Vito and Gracia soils. Applied $CaCO_3$ increased total herbage from the Colombian soils, Cararao, Drainageway, and East Carimagua. Frit added to Drainageway soil increased total yields at all lime rates. Extra P increased total Pangola forage from Agronomy Area, Carerao, and East Carimagua soils. Application of $CaCO_3$ increased forage Ca, but decreased Zn and Mn in Pangola. Additional P increased P and decreased Zn concentrations in the forage. Pangola response to applied lime in Colombian soils may have been related to reduction of exchangeable and soluble Al and/or low available Ca in unlimed soils. Following application of additional Mg, herbage yields and

Mg concentrations from Colombian soils from the sixth through the eight harvests increased markedly over yields from earlier harvests.

Initial soil and plant data indicated the possibility of Zn and/or Cu deficiency in East Carimagua and Drainageway soils. Therefore, a Zn x Cu experiment was established with these soils using Pangola as the test plant. Copper added to East Carimagua increased total yields of Pangola herbage from the third harvest. Although applied Zn did not significantly increase yields in this soil, maximum growth was obtained when both Zn and Cu were applied at 5 ppm. Application of Zn and Cu to Drainageway soil increased oven-dry Pangola herbage from the second and third harvests and total forage produced. Maximum yields were obtained with application of 5 ppm Zn and 60 ppm Cu. Copper applied to the Drainageway soil reduced concentrations of most nutrients, except Cu. However, total uptake of nutrients was not affected by this treatment, indicating that depression in forage nutrient concentrations was caused by dilution from increased growth. On the other hand, added Zn reduced forage concentrations of all nutrients, except Zn. This treatment depressed total uptake of Mg, P, and Ca, but increased Zn and Fe uptake. The marked reductions in P concentrations and uptake by Zn applications may be an important problem in tropical soils which are low in available P and which also require Zn additions to obtain maximum yields. Only 5 ppm of Zn were required to provide a sufficient supply of this element, but the adverse effect of Zn on P concentrations and uptake was striking even though 400 ppm of P were applied.

Results from these experiments indicate that the critical Zn concentration in Pangola forage is between 10 to 13 ppm, and Cu between 2.0 and 3.2 ppm.

Regression analyses for herbage yields for the second and third harvests, total herbage produced, and herbage P and Mg concentrations from the first and second harvests from Drainageway soil showed that the quadratic model fitted the regression equations for all variables better than the linear model.

The results obtained warrant the following conclusions:

1. Critical Cu concentrations in oven-dry herbage were 2.5 ppm for bahia, and between 2.0 and 3.2 ppm for Pangola. The critical Zn concentration for Pangola was between 10 and 13 ppm.

2. Soils from Costa Rica and Colombia used in these studies are dominated by colloids bearing a constant

surface potential as indicated by their highly pH-dependent CEC.

3. The Costa Rican soils studied contained enough available Ca as a nutrient for plant growth. However, these soils may require lime as an amendment when plant species sensitive to high Mn concentrations are planted. Plants classified as being very sensitive to exchangeable and soluble Al may also require application of $CaCO_3$ as a soil amendment.

4. The Colombian soils studied may require Ca as a nutrient for plants that are not efficient in obtaining Ca from soils with limited quantities of this element.

5. Lime applications may also be required in these Colombian soils to obtain optimum growth of plants that are not tolerant of high concentrations of exchangeable and soluble Al. The amount of $CaCO_3$ required will depend on the type and quantities of soil colloids, and the level of exchangeable Al tolerated by the crop plant. Generally, no more than 1/3 the theoretical amount of lime required to increase soil pH to 6.4, as determined by the SMP method, will be required for growing tropical crops.

6. Some Colombian soils may require Zn and/or Cu applications to obtain maximum yields.

7. Zinc depressed uptake of P and Mg by plants from Colombian soils; interactions between Zn and these nutrients must be studied and optimum application rates determined.

8. Whereas liming, and N and P fertilization are expected to be required immediately for intensified crop production on these soils from the eastern Llanos of Colombia, results from greenhouse studies indicate that Mg may become deficient following initiation of cropping.

9. Soils from Colombia contained low concentrations of nutrients, but the data obtained indicate that proper fertilization and management will make them highly productive.

APPENDICES

APPENDIX A

TABLES 38 AND 39

Table 3E--Field descriptions of soil profiles from Costa Rica

Depth, cm	Morphology
	Profile 1
	Location: San Vito de Java, Costa Rica Soil Order. Ultisol Remarks. Samples taken at the top of a small hill in a well-drained area that had been planted to corn 4-5 years previously. The sampling site was located in a dense cover of trees and shrubs close to the road from San Vito to Paso Real de Terraba. No limestone was present, but occasional small andesitic outcrops were noted along the road.
0-8	Dark brown (7.5YR 3/2) loam; moderate, medium crumb structure; extremely friable; profuse roots and earthworms; smooth boundary.
8-36	Dark brown (7.5YR 3/2) loam; very weak subangular blocky breaking easily to weak fine crumb structure; very friable; common roots; smooth boundary.
36-76	Brown to dark-brown (7.5YR 4/4) clay loam; weak medium subangular blocky structure; friable, non-sticky, slightly plastic; few roots.
76-91	Yellowish-red (5YR 5/8) clay loam; weak, medium subangular blocky structure; firm; very few roots.
91-122	Mottled yellowish-red (5YR 5/8), strong brown (7.5YR 5/8), and some red (2.5YR 4/8) clay loam; massive structure, firm.
122-152	Mottled light grey (2.5Y 7/2), weak red (7.5R 4/4), and yellowish-brown (10YR 5/8) clay; massive structure; very firm, no roots.

Table 38 (Continued)

Depth, cm	Morphology
	Profile 2
	Location: San Isidro del General, Costa Rica Soil Order: Oxisol Remarks: Samples taken from area covered by native vegetation of an old land surface 46.3 km south of San Isidro on west side of Panamerican highway. The vegetation was estimated to be at least 6 years old. Samples were taken on a slight slope (3-5%) towards top but not on top of break. There was an established improved pasture approximately 50 m from sample site.
0-5	Dusky red (2.5YR 3/2) clay loam; fine crumb structure; very friable; many roots but no earthworms evident; smooth boundary. Surface thickness extremely variable over short linear distances.
5-30	Reddish-brown (2.5YR 4/4) clay loam; massive structure; very friable; common roots; clear, smooth boundary
30-60	Red (10R 4/6) clay; massive structure; firm, few roots.
60-100	Red (10R 4/6) clay; massive structure, firm; very few roots.
100-150	Reddish-brown (5YR 4/4) clay; massive structure, firm; no roots, some Mn concretions.
150-180	Reddish-brown (5YR 4/4) clay; massive structure; firm; no roots; common Mn concretions.

Table 38 (Continued)

Depth, cm	Morphology
	Profile 3
	Location. Grecia, Costa Rica Soil Order: Ultisol Remarks: Samples collected in a pasture 4 km southwest of Grecia on road to Argentina and Atenas. Considered typical of "red Latosols" in this area.
0-36	Dark reddish-brown (5YR 3/2) loam; moderate, medium subangular blocky structure; very friable; common roots; smooth boundary.
36-90	Dark reddish-brown (5YR 3/4) clay; moderate, medium subangular blocky structure; friable to firm; few roots.
90-183	Dark reddish-brown (5YR 3/4) clay loam; moderate, medium subangular blocky structure; very few roots.
183-213	Dark reddish-brown (5YR 3/4) clay loam; weak, subangular blocky structure; friable to firm; very few roots.

Table 38 (Continued)

Depth, cm	Morphology
	Profile 4
	Location. Alajuela, Costa Rica Soil Order: Ultisol Remarks. Samples taken approximately 1 km northwest of Alajuela on road from Alajuela to Pueblo Nuevo and Santa Elena. Collected in an old bedded field presently under pasture
0-13	Dark reddish-brown (5YR 3/3) loam, fine crumb structure, loose; many roots; gradual smooth boundary.
13-50	Dark reddish-brown (5YR 3/3) loam, weak, fine subangular blocky structure; friable; many roots; clear smooth boundary.
50-80	Dark reddish-brown (5YR 3/4) clay loam; weak, medium subangular blocky structure; friable; common roots.
80-120	Reddish-brown (5YR 4/4) clay loam; moderate, medium subangular blocky structure; firm; few roots. Manganese streaks (black) increase with depth.
120-150	Dark reddish-brown (5YR 3/2) clay loam; moderate, medium, subangular blocky structure; firm; very few roots.

Table 39--Field descriptions of soil profiles from Colombia

Depth, cm	Morphology
	Profile 5
	Location. Agronomy area, Carimagua, Colombia Soil order. Oxisol Remarks: Samples taken on an old land surface 1 km west of houses of Agricultural Experiment Station, I. C. A. headquarters. Well-drained area of non-dissected high plains.
0-13	Dark brown (7.5YR 3/2) clay loam; moderate, medium subangular blocky structure, friable; common roots smooth clear boundary. Many earthworms casts on surface.
13-26	Brown to dark brown (7.5YR 4/4) clay loam; weak, medium subangular blocky structure breaking to fine crumb; friable; common roots.
36-80	Strong brown (7.5YR 5/6) clay loam or clay; massive structure; slightly plastic; few roots.
80-178	Red (2.5YR 5/8) clay, massive structure, slightly plastic; very few roots.
178-188$^+$	Red (10R 5/6) clay; massive structure; slightly plastic, common, soft, red (10R 4/8) plinthic nodules.

Table 39 (Continued)

Depth, cm	Morphology
	Profile 6
	Location: Cararao creek, Carimagua, Colombia Soil Order: Ultisol Remarks: Samples collected in wooded area approximately 800 m from creek head and 30 m from creek bed. This is an alluvial soil used mainly for shifting cultivation.
0-10	Very dark grayish-brown (10YR 3/2) clay; weak, medium subangular blocky structure; friable, many roots; smooth gradual boundary.
10-46	Dark gray (10YR 4/1) clay; massive structure; firm; common roots.
46-107	Brown (7.5YR 5/2) clay; massive structure, firm; few roots. Few faint strong brown (7.5YR 5/8) mottles.
107-183	Brown (7.5YR 5/2) clay with small red (10R 4/6) prominent mottles; massive structure. firm.

Table 39 (Continued)

Depth, cm	Morphology
	Profile 7
	Location: Drainageway, Carimagua, Colombia Soil Order: Oxisol Remarks. Samples taken approximately 250 m southwest of lake and 20 m east of the canal. Poorly drained soil with many termite mounds approximately 45 cm high.
0-20	Black (10YR 2/1) loam to clay loam; weak, medium subangular blocky structure; very friable; smooth clear boundary.
20-76	Pinkish-gray (7.5YR 6/2) loam; massive structure; plastic.
76-183	Mottled pale brown (10YR 6/3), red (10R 5/8), and brown (10YR 5/3) clay; massive structure; plastic. Few soft plastic nodules up to 0.64 cm in diameter, increasing with depth.
183-213	Mottled pale brown (10YR 6/3), red (10YR 4/8), and light brownish-gray (10YR 6/2) clay, massive structure, plastic. Numerous soft red (10R 4/8) plinthic nodules.

Table 39 (Continued)

Depth, cm	Morphology
	Profile 8
	Location: East Carimagua, Colombia Soil Order: Ultisol Remarks: Samples collected 15.3 cm east of Carimagua Agricultural Experiment Station on the road to Alegria.
0-13	Dark brown (7.5YR 3/2) sandy loam; weak, coarse crumb structure; friable; common roots; smooth gradual boundary.
13-25	Yellowish-red (5YR 4/6) sandy loam; weak, medium subangular blocky structure; friable smooth diffuse boundary.
25-107	Red (2.5YR 5/8) sandy clay loam; massive structure; friable. Crushes to small particles without definite shape.
107-213	Red (10R 5/8) sandy clay loam; massive structure; friable. Crushes to small particles without definite shape.

APPENDIX B

TABLES 40 THROUGH 45

Table 40--Effect of zinc and copper in East Carimagua soil on yields of Pangola harbage, and 0.1$\underline{N}$ HCl extractable micronutrients*

Zn	Cu	Oven-dry herbage				Soil micronutrients†			
applied		Harvests							
		1	2	3	Total	Cu	Zn	Mn	Fe
---ppm --		g/pot				ppm			
0.0	0.0	3.7a	7.7a	3.2b	14.7abcd	0.25f	0.47h	0.38abc	22a
0.0	2.5	3.2a	6.0a	2.9b	12.1cd	2.75de	0.44h	0.31bc	19a
0.0	5.0	4.0a	6.8a	4.1ab	14.9abcd	4.81c	0.42h	0.25c	21a
0.0	10.0	3.8a	8.1a	3.9ab	15.8abc	4.10cd	0.53h	0.25c	20a
2.5	0.0	2.3a	7.6a	3.7ab	13.6bcd	0.25f	3.23ef	0.25c	21a
2.5	2.5	3.1a	8.2a	4.0ab	15.2abcd	3.56cd	3.06def	0.38abc	23a
2.5	5.0	2.5a	7.2a	3.9ab	13.6bcd	4.81c	2.61f	0.25c	17a
2.5	10.0	3.1a	7.8a	3.8ab	14.6abcd	8.19ab	2.31fg	0.31bc	18a
5.0	0.0	3.1a	6.1a	2.4b	11.6d	0.38ef	4.81cde	0.38abc	18a
5.0	2.5	3.5a	7.8a	3.6ab	15.0abcd	3.75cd	6.56c	0.31bc	20a
5.0	5.0	4.2a	9.4a	4.7a	18.2a	5.88bc	5.80c	0.25c	19a
5.0	10.0	3.2a	7.6a	4.1ab	14.9abcd	10.55a	5.46cd	0.31bc	21a
10.0	0.0	3.3a	7.4a	3.7ab	14.4abcd	0.31ef	12.58a	0.31bc	20a
10.0	2.5	4.0a	8.0a	3.9ab	15.9abc	2.75de	17.15a	0.25c	19a
10.0	5.0	4.1a	8.2a	3.9ab	16.2ab	5.50c	15.58a	0.44ab	20a
10.0	10.0	4.2a	8.4a	3.9ab	16.5ab	8.63a	10.33a	0.50a	21a

*Values within a column followed by different letters are significantly different at the 0.05 probability level.

†Soil samples were taken following the second Pangola harvest.

Table 41--Effect of zinc and copper in East Carimagua soil on nutrient concentrations in Pangola herbage

Zn	Cu	Oven-dry herbage*							
Applied		Ca	Mg	P	K	Cu	Zn	Mn	Fe
--- ppm --		------------- %			-------------	------------- ppm			-------------
0.0	0.0	0.24a[+]	0.32a	0.16ab	2.23f	3.2a	32fgh	50abcde	87a
0.0	2.5	0.23a	0.28a	0.14b	2.45d	5.0bc	30fgh	46abcde	69abc
0.0	5.0	0.25a	0.31a	0.15b	2.06g	4.7cd	26h	43bcde	69abc
0.0	10.0	0.23a	0.31a	0.16ab	2.08ef	6.3ab	28gh	48abcde	72abc
2.5	0.0	0.25a	0.32a	0.46ab	2.93a	4.4cde	43defg	55abcd	81ab
2.5	2.5	0.25a	0.30a	0.15b	2.79b	4.4cde	39efgh	52abcde	66bc
2.5	5.0	0.24a	0.30a	0.15b	2.90a	5.3abc	41efgh	61a	73abc
2.5	10.0	0.26a	0.30a	0.15b	2.62c	6.3ab	45def	59abc	73abc
5.0	0.0	0.24a	0.30a	0.13a	2.64c	3.5de	65abc	60ab	72abc
5.0	2.5	0.21a	0.29a	0.16ab	2.36de	5.0bc	58bcd	48abcde	69abc
5.0	5.0	0.24a	0.33a	0.16ab	2.11g	5.7abc	50cde	51abcde	66bc
5.0	10.0	0.22a	0.30a	0.16ab	2.69bc	6.6a	62abc	53abcde	61bc
10.0	0.0	0.23a	0.29a	0.14b	2.30ef	3.2a	74ab	52abcde	69abc
10.0	2.5	0.26a	0.32a	0.14b	2.05g	5.0bc	79a	42cde	65bc
10.0	5.0	0.23a	0.32a	0.14b	2.09g	5.0bc	65abc	41de	60c
10.0	10.0	0.22a	0.28a	0.14b	2.46d	6.3ab	77a	37e	68abc

*Nutrient concentrations are for the first harvest.

[+] Values within a column followed by different letters are significantly different at the 0.05 probability level.

Table 42--Effect of zinc and copper in East Carimagua soil on nutrient concentrations in Pangola herbage

Zn	Cu	Oven-dry herbage*							
applied		Ca	Mg	P	K	Cu	Zn	Mn	Fe
--- ppm --		------------- %			------------	-------------	ppm		----------
0.0	0.0	0.31a$^+$	0.51a	0.11c	1.40a	1.6f	18h	14d	58a
0.0	2.5	0.32a	0.57a	0.15a	2.05a	4.1ab	21gh	24ab	75a
0.0	5.0	0.31a	0.49a	0.11c	1.40a	2.8cdef	22gh	18abcd	68a
0.0	10.0	0.31a	0.50a	0.11c	1.30a	4.1ab	21gh	16bcd	72a
2.5	0.0	0.33a	0.54a	0.14ab	1.82a	2.5def	29efgh	23abc	82a
2.5	2.5	0.32a	0.50a	0.13ab	1.56a	3.5abcd	27fgh	17abcd	80a
2.5	5.0	0.30a	0.53a	0.13ab	1.66a	3.8abc	28efgh	20abcd	70a
2.5	10.0	0.31a	0.50a	0.11c	1.65a	4.1ab	33efg	20abcd	107a
5.0	0.0	0.29a	0.52a	0.14ab	1.91a	1.8f	52b	20abcd	96a
5.0	2.5	0.29a	0.49a	0.11c	1.52a	3.2bcde	36cdefg	24ab	78a
5.0	5.0	0.28a	0.46a	0.10c	1.15a	3.2bcde	34defg	23abc	69a
5.0	10.0	0.28a	0.49a	0.12bc	1.63a	4.7a	41bcdef	25a	77a
10.0	0.0	0.29a	0.47a	0.12bc	1.52a	2.2ef	68a	19abcd	82a
10.0	2.5	0.28a	0.45a	0.10c	1.52a	2.8cdef	50bc	18abcd	81a
10.0	5.0	0.30a	0.51a	0.10c	1.59a	3.2bcde	43bcde	15cd	60
10.0	10.0	0.28a	0.47a	0.10c	1.38a	2.8cdef	49bcd	12d	63a

*Nutrient concentrations are for the second harvest.

+Values within a column followed by different letters are significantly different at the 0.05 probability level.

Table 43--Effect of zinc and copper in Drainageway soil on yields of Pangola herbage, and 0.1N HCl extractable micronutrients*

Zn	Cu	Oven-dry herbage				Soil micronutrients†			
		Harvests							
applied		1	2	3	Total	Cu	Zn	Mn	Fe
---ppm---		------------ g/pot ------------				------------ ppm ------------			
0	0	3.9a	3.1de	2.4cd	9.4d	0.25ef	0.71f	1.44c	2.25fg
0	15	3.7a	3.9d	2.7bc	10.3d	0.31def	0.69f	1.44c	1.96g
0	30	4.5a	4.7cd	3.3abc	12.5bcd	0.50de	0.71f	1.44c	2.55efg
0	60	3.7a	4.7cd	2.5cd	10.9cd	1.19c	0.72f	1.63abc	2.48efg
5	0	3.9a	4.5d	2.1cd	10.4d	0.19ef	2.69e	1.56abc	2.51efg
5	15	5.0a	7.6ab	4.5ab	17.1ab	0.38def	3.22cde	1.63abc	3.65ab
5	30	4.1a	8.9a	3.0bc	15.9abc	0.50de	2.47ef	1.81ab	3.65ab
5	60	4.1a	8.8a	5.9a	18.8a	1.63ab	3.17de	1.75abc	3.83a
10	0	3.7a	5.9bcd	2.6cd	12.1bcd	0.25ef	3.28cde	1.69abc	3.19bcd
10	15	4.2a	7.1abc	3.3abc	14.6abcd	0.31def	5.05cd	1.88a	2.91cde
10	30	3.6a	8.5a	4.6ab	16.7ab	0.44def	4.87cd	1.75abc	3.71ab
10	60	3.8a	8.1ab	5.4ab	17.4ab	1.38bc	5.13c	1.81ab	3.35abc
20	0	3.8a	4.7cd	1.8d	10.2d	0.06f	8.80b	1.69abc	2.60def
20	15	3.7a	7.7ab	3.3abc	14.7abcd	0.38def	15.14a	1.56abc	2.44efg
20	30	4.6a	7.5ab	3.8abc	15.9abc	0.69d	13.83a	1.50bc	2.25fg
20	60	4.3a	7.3ab	3.3abc	15.7abc	1.81a	14.33a	1.68abc	2.66def

*Values within a column followed by different letters are significantly different at the 0.05 probability level.
†Soil samples were taken following the second Pangola harvest.

Table 44--Effect of zinc and copper in Drainageway soil on nutrient concentrations in Pangola herbage

Zn	Cu	Oven-dry herbage*								
applied		Ca	Mg	P	K	Cu	Zn	Mn	Fe	B
---ppm---				%				ppm		
0	0	0.41a[+]	0.19b	0.28a	2.19bcde	2.6fg	13gh	57abc	103b	5.0a
0	15	0.43a	0.22a	0.30a	2.49ab	6.6bcd	17gh	63a	141a	--
0	30	0.41a	0.16cd	0.21b	1.89de	4.4ef	10h	56abc	80bcde	--
0	60	0.36b	0.18bc	0.21b	2.01bcde	7.5ab	13gh	51abc	84bcde	4.3b
5	0	0.38ab	0.13e	0.17c	2.06bcde	2.5fg	29ef	48abc	86bcde	--
5	15	0.36bc	0.13e	0.15cd	2.37abcd	4.7de	27ef	44cd	86bcde	--
5	30	0.36bc	0.12e	0.14cd	2.47ab	5.7cde	24fg	54abc	78cde	--
5	60	0.36bc	0.13e	0.15cd	2.76a	6.3cde	25fg	49abc	71de	--
10	0	0.39ab	0.13e	0.17c	2.70a	1.0g	51cd	53abc	91bcd	4.8a
10	15	0.36bc	0.14de	0.16cd	2.77a	5.0de	39de	47bc	84bcde	--
10	30	0.38ab	0.13e	0.14cd	2.42abc	5.0de	30ef	60ab	73de	--
10	60	0.36bc	0.12e	0.13d	2.35abcd	8.5ab	34ef	60ab	66ee	--
20	0	0.35c	0.14de	0.16cd	2.36abcd	2.3g	89a	52abc	97bc	--
20	15	0.35c	0.14de	0.14cd	1.78e	5.3de	61bc	44cc	66e	--
20	30	0.38ab	0.14de	0.14cd	1.95cde	6.6bcd	59bc	46bc	77cde	--
20	60	0.36bc	0.14de	0.14cd	2.03bcde	8.8a	64b	43c	75cde	5.3a

*Nutrient concentrations are for the first harvest.

[+]Values within a column followed by different letters are significantly different at the 0.05 probability level.

Table 45--Effect of zinc and copper in Drainageway soil on nutrient concentrations in Pangola herbage

Zn	Cu	Oven-dry herbage*							
applied		Ca	Mg	P	K	Cu	Zn	Mn	Fe
---ppm---		%				ppm			
0	0	0.82a[+]	0.60a	0.59a	2.63a	2.2efg	12hi	65a	114a
0	15	0.71b	0.60a	0.56ab	2.97a	7.9a	9i	70a	120a
0	30	0.68bc	0.57ab	0.50b	2.58ab	8.4a	10i	66a	91abc
0	60	0.60cd	0.48b	0.28c	2.56abc	8.8a	9i	66a	98ab
5	0	0.50defg	0.26cdef	0.19d	2.47abcd	1.9fg	23def	56ab	81bc
5	15	0.47efgh	0.20defg	0.13d	1.39e	3.2def	14fghi	36cd	66bc
5	30	0.39hi	0.18g	0.13d	1.76cde	3.5de	16fghi	38cd	71bc
5	60	0.36h	0.16g	0.11d	1.37e	3.8cd	13ghi	28d	65c
10	0	0.51def	0.22defg	0.14d	2.11bcde	1.6g	32cd	43bcd	76bc
10	15	0.43fghi	0.18g	0.13d	1.51e	3.5de	21efgh	36cd	66bc
10	30	0.41fghi	0.19fg	0.13d	1.76cde	4.4bcd	22efg	45bc	62c
10	60	0.40ghi	0.19fg	0.15d	1.83bcde	5.2bc	29de	45bc	64c
20	0	0.54de	0.34c	0.17d	2.39abcd	1.6g	71a	46bc	91abc
20	15	0.45efgh	0.28cd	0.12d	1.67de	5.7b	39bc	40bcd	120a
20	30	0.49efgh	0.26cdef	0.11d	1.46e	4.7bcd	43b	38cd	81bc
20	60	0.44efghi	0.27cde	0.09d	1.45e	5.3bc	48b	37cd	67bc

Nutrient concentrations are for the second harvest.

[+] Values within a column followed by different letters are significantly different at the 0.05 probability level.

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BIOGRAPHICAL SKETCH

Marciano Rodriguez-Gomez was born on November 12, 1936 in Chiriqui, Panama. He attended high school at the Colegio Felix Olivares C. and graduated in 1955. In July 1957, he entered the Escuela Agricola Panamericana in Honduras, C. A. where he received his Agronomo degree in 1960.

He worked for the Research Department of the Tela Railroad Company, a subsidiary of United Fruit Company, from 1960 to 1963. In September 1963, he entered the University of Florida and obtained the degree of Bachelor of Science in Agriculture in the Agronomy Department in April 1965.

From May 1965 through June 1969, he worked for the Tela Railroad Company in Honduras as Senior Research Assistant. In June 1969, he was awarded a fellowship by the United Fruit Company Foundation (United Brands Foundation) and an Assistantship by the Agronomy Department of the University of Florida to continue his studies and obtained a Master of Science degree in Agriculture in

June 1971 He then continued his studies in the Department of Soil Science, University of Florida, financed partially by the United Brands Foundation and by the Center for Tropical Agriculture. Presently he is a candidate for the degree of Doctor of Philosophy.

He is married to the former Ana Maria Rosales and is the father of two children, Ana Isabel and Javier Roberto. He is a member of Alpha Zeta Honorary Fraternity, the Soil Science Society of America, the American Society of Agronomy, the International Society of Soil Science, and the Soil and Crop Science Society of Florida.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

William G. Blue

William G. Blue, Chairman
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Gerald O. Mott

Gerald O. Mott
Professor of Agronomy

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Sherlie H West

Sherlie H. West
Professor of Agronomy and
Assistant Dean

This di[illegible] to the Dean of the College of Agricu[illegible] Council and was accepted as partial [illegible] requirements for the degree of Doctor of Phi[illegible]

December, 1974

Dean, College of Agriculture

Dean, Graduate School